ADA042121

AFAPL-TR-77-32

ADVANCED HIGH SPEED ROLLER BEARING INSPECTION TECHNIQUES

TRW DEFENSE AND SPACE SYSTEMS GROUP
ONE SPACE PARK
REDONDO BEACH, CALIFORNIA 90278

MAY 1977

TECHNICAL REPORT AFAPL-TR-77-32
FINAL REPORT FOR PERIOD NOVEMBER 1976 - APRIL 1977

Approved for public release; distribution unlimited

AD No.
DDC FILE COPY

DDC
RECEIVED
JUL 27 1977
D

AIR FORCE AERO-PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any be related thereto.

This report has been reviewed by the Information Office (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

James F. Dill

JAMES F. DILL
Project Engineer

FOR THE COMMANDER

Howard F. Jones

HOWARD F. JONES
Chief, Lubrication Branch
Fuels & Lubrication Division

Copies of this report should not be returned unless return is required by security consideration, contractual obligation, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFAPL-TR-77-32	2. GOVT ACCESSION NO. / 3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): ADVANCED HIGH SPEED ROLLER BEARING INSPECTION TECHNIQUES.	5. TYPE OF REPORT & PERIOD COVERED: Final Report, 30 Oct 76 - 1 Apr 77
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Jerold L. Jacoby, Jack R. Bohn	8. CONTRACT OR GRANT NUMBER(s): F33615-76-C-2147
9. PERFORMING ORGANIZATION NAME AND ADDRESS: TRW Defense and Space Systems Group, One Space Park, Redondo Beach, California 90278	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Project No. 3048, Task No. 304806, Work Unit No. 30480695
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Aero-Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio	12. REPORT DATE: May 1977
	13. NUMBER OF PAGES: 78 (12) 80
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Roller Bearings
Bearing Inspection
Automated Inspection

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A comprehensive survey of state-of-the-art precision measurement techniques applicable to dimensional inspection of rollers for high speed bearings (greater than 2.0 million DN) was undertaken. Particular attention was given to noncontacting techniques which would permit automated 100% inspection of the rollers for use in such bearings. The measurement techniques were evaluated to determine their utility for incorporation into a cost-effective roller inspection system. A concept for a fully automated roller inspection

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

401 571

20. ABSTRACT (Continued)

system is described. It provides for the preparation, inspection, re-oiling and sorting of the rollers with minimal human supervision. The system is conceived to be self-contained so that it can operate independent of environmental constraints. It can be developed by adapting existing technology to the specific requirements for roller inspection.

FOREWORD

This technical report was submitted by the TRW Defense and Space Systems Group under Contract F33615-76-C-2147. The effort was sponsored by the Air Force Aero-Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project 3048 (Aerospace Fuels and Lubrication), Task 304806 (Aerospace Lubrication) and Work Unit 30480695 (Advanced High Speed Roller Bearing Inspection Techniques). Total funding for this project was provided from Laboratory Directors Funds. Dr. James F. Dill/AFAPL/SFL administered the project for the Air Force. Mr. Jack R. Bohn and Mr. Jerold L. Jacoby of TRW Defense and Space Systems Group were technically responsible for the work.

ACCESSION for
NTIS White Section
DDC Buff Section
UNANNOUNCED
JUSTIFICATION
BY
DISTRIBUTION/AVAILABILITY CODES
Dist. Avail. and/or Special
A

TABLE OF CONTENTS

PRECEDING PAGE BLANK-NOT FILMED

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

1.0 INTRODUCTION AND SUMMARY

A recent investigation conducted by the Air Force indicated a need for improved inspection techniques to reduce the cost of inspecting rollers for high speed aircraft engine bearings. Operating speeds of turbines have increased and the tolerances required for the production of bearing components are becoming tighter. At the present time, tolerances are such that their reliable measurement is questionable in terms of ultimate performance required in the near future. The cost effectiveness of bearing manufacturing could be improved dramatically if adequate automated bearing inspection methods were available. The objective of this program has been to determine the feasibility of developing such an inspection system utilizing existing technology. A comprehensive survey of state-of-the-art precision measurement techniques applicable to automated inspection of rollers was undertaken. These measurement techniques were evaluated to determine their feasibility for incorporation into a cost-effective roller inspection system. Finally, a measurement concept has been selected which can serve as the basis for the further development and subsequent demonstration of a roller inspection system.

Although improvements are currently needed for improved inspection of a wide range of aircraft quality bearings, this study concentrated on rollers from a single bearing which is of current interest. These rollers (from the No. 4 main shaft bearing of the F-100 engine) are representative of those which pose problems for current inspection techniques. The necessity of adapting any measurement system for use with a larger class of rollers has been considered throughout.

Contacting measurement techniques have been developed and employed for many years, thus their capabilities are well established. In order to advance the level of sophistication of roller measurements, it was decided to concentrate the efforts of this investigation on the identification and evaluation of techniques which have not been traditionally used for roller inspection. In particular, efforts have been focused on noncontacting measurement techniques. These techniques have the added advantage of insuring against possible damage of the roller during the inspection process while permitting rapid measurements.

Over two hundred potential suppliers of measuring devices were contacted in an attempt to survey the state-of-the-art in precision measurement techniques. The techniques considered ranged from fairly standard methods such as air gauging to newer non-traditional approaches such as holographic interferometry. Devices available "off-the-shelf" which required little or no modification to adapt to this problem were favored. However, new techniques still under development were also considered. The survey yielded approximately thirty candidate devices. These came from three basic technology areas: electromagnetics, pneumatics and optics. The capabilities of these devices were evaluated to determine the feasibility of their incorporation into a roller inspection system.

The survey and evaluation of non-contacting measurement techniques produced several alternative approaches for performing the required inspection tasks. Although no one technique was found which could adequately measure all of the roller characteristics, at least two techniques for measuring each characteristic were identified. These techniques overlap so that several related measurements can be performed together.

A concept for a fully automated roller inspection system has been developed. It provides for the preparation (which includes cleaning and temperature stabilization), inspection, re-oiling and sorting of the rollers with minimal human supervision. The heart of the system is a rotary turntable which introduces the roller into the measurement stations located around its circumference. All of the roller characteristics are measured at three stations which employ various combinations of measurement techniques. A microcomputer serves as the basis for monitoring and controlling all system functions as well as collecting and sorting the measurement data.

The goal of producing a fully automated roller inspection system is achievable using current technology. Critical evaluations need to be performed to verify the capabilities of the selected measurement devices to function adequately in a manufacturing environment. These laboratory tests will aid in the final selections among techniques which, at present, appear to have equivalent capabilities. Breadboards of the measurement stations will then be further demonstrated prior to the final design and fabrication of a prototype roller inspection system. It is estimated that such a fully automated 100% inspection of the roller characteristics will result in a minimum 45% reduction in the cost of the rollers.

2.0 PRECISION MEASUREMENTS OF ROLLERS

It is necessary to understand the nature of the roller inspection problem before steps can be taken to solve it. Knowledge of the techniques used to fabricate the rollers, current inspection procedures and anticipated measurement tolerances is required. This background can then serve as a foundation for developing a cost-effective inspection procedure.

2.1 Roller Measurement Requirements

In order to proceed with the development of an automated inspection system for bearing rollers, it is first necessary to examine the properties of the rollers and the requirements which are placed upon the inspection. Parameters such as the geometry and material properties of the rollers may determine which measurement techniques are considered.

The locations of the various roller characteristics which are of interest are shown with the diagram of a roller in Figure 2.1. Table I shows the "typical" measurement tolerances which were used as a guide for establishing the acceptance criteria for the measurement devices. The thirteen specifications shown in Table I have been divided into six sub-groups each containing parameters which can be measured by similar means. For example, in Group I, the OD taper can be determined by measuring the diameter at two points along the cylindrical flat part of the roller. The cylindricity (or out-of-roundness) is how the diameter varies when measured at points around the circumference of the roller. Similarly, for Group II, end runout is a measure of the squareness of the plane end to a line through the center of the roller. End parallelism can be computed from the relative squareness of the two ends and the length is the separation of the end planes. If the location of the two end planes can be measured, then all three of these parameters are determined. The parameters in the other groups are similarly related.

A second feature of the groupings in Table I is the range of the tolerances. This is most apparent from a quick comparison of Groups I and V, where the tolerances differ by three orders of magnitude. It is

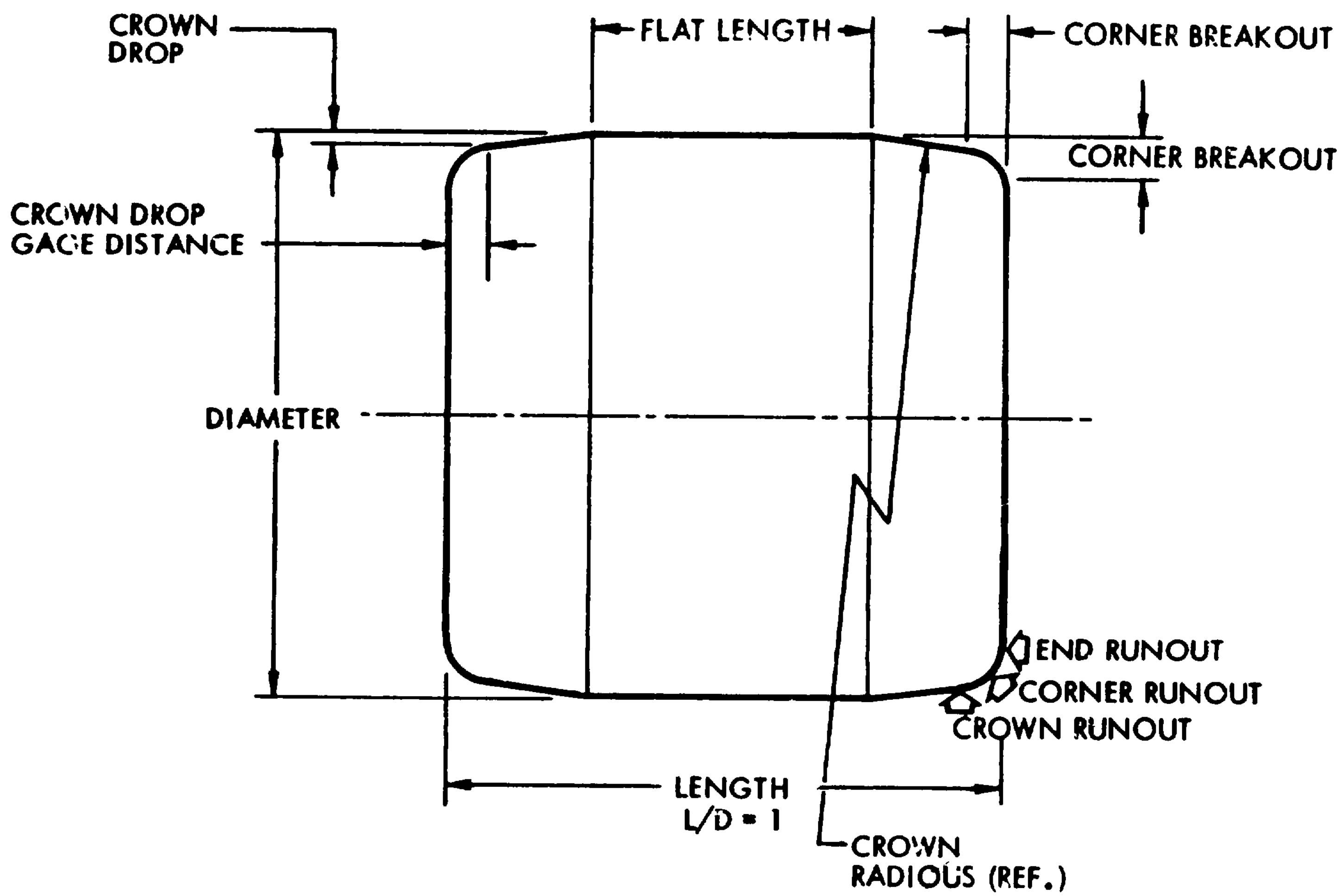


Figure 2.1. Relative Locations of the Roller Characteristics to be Measured.

likely that the techniques used to measure the diameter will be too sensitive to measure the flat length. The technique for flat length will not have the sensitivity required to measure the diameter. The implication is that there is a logical separation into several different measuring problems, each of which will likely require a separate solution.

TABLE I

TOLERANCES FOR MEASUREMENT OF ROLLER CHARACTERISTICS

GROUP I	DIAMETER	10μ"
	OD TAPER	10μ"
	CYLINDRICITY	50μ"
GROUP II	LENGTH	200μ"
	END PARALLEL	50μ"
	END RUNOUT	50μ"
GROUP III	CROWN DROP	100μ"
	CROWN RUNOUT	50μ"
GROUP IV	CORNER BREAKOUT	500μ"
	CORNER RUNOUT	500μ"
GROUP V	FLAT LENGTH	39,000μ"
	FLAT CENTRALITY	30,000μ"
GROUP VI	SURFACE FINISH	3AA

The requirement exists to be able to inspect rollers having a considerable range of sizes and other characteristics which are representative of those encountered in aircraft quality bearings. However, in attempting to deal with a range of rollers, the techniques proposed and the tolerances discussed tend to become ambiguous. Rather than discuss generalities, it is more productive to consider a specific case which is representative of the overall problem. This specific case is in fact representative and the techniques developed can be readily adapted for use with other rollers of interest.

The roller from the No. 4 main shaft bearing of the F-100 engine was selected for use as a model in this study. As such, it is referred to repeatedly throughout this report. Figure 2.2 shows a photograph of this particular bearing. Two of the individual rollers from this bearing are shown in Figure 2.3. The dimensions of this roller (MRC part #RLD162783C) are shown in Table II, along with the relative accuracies required. This accuracy was obtained by dividing the dimension by the allowable tolerance shown in Table I. The range of numbers in this column reinforce the point made earlier concerning the large variance in the required measurement accuracies for the different roller characteristics.

TABLE II

DIMENSIONS OF ROLLER FROM
F-100 No. 4 MAIN SHAFT BEARING

ROLLER CHARACTERISTIC	DIMENSION	ACCURACY REQUIRED*
Diameter	.6299"	1 part in 63,000
Length	.6299"	1 part in 3,150
Crown Drop	.0018"	1 part in 18
Corner Breakout	.035"	1 part in 70
Flat Length	.1890"	1 part in 5

*Accuracy derived by dividing dimension shown on this table by the corresponding tolerance from Table I.

2.2 Current Roller Inspection Procedures

A knowledge of current roller inspection procedures can serve as a basis for understanding the problem and the development of a cost-effective alternative solution. Each inspection operation described below requires that the rollers be picked up individually from a container for inspection purposes and, after the completion of the inspection

Figure 2.2. No. 4 Main Shaft Bearing from the F-100 Engine

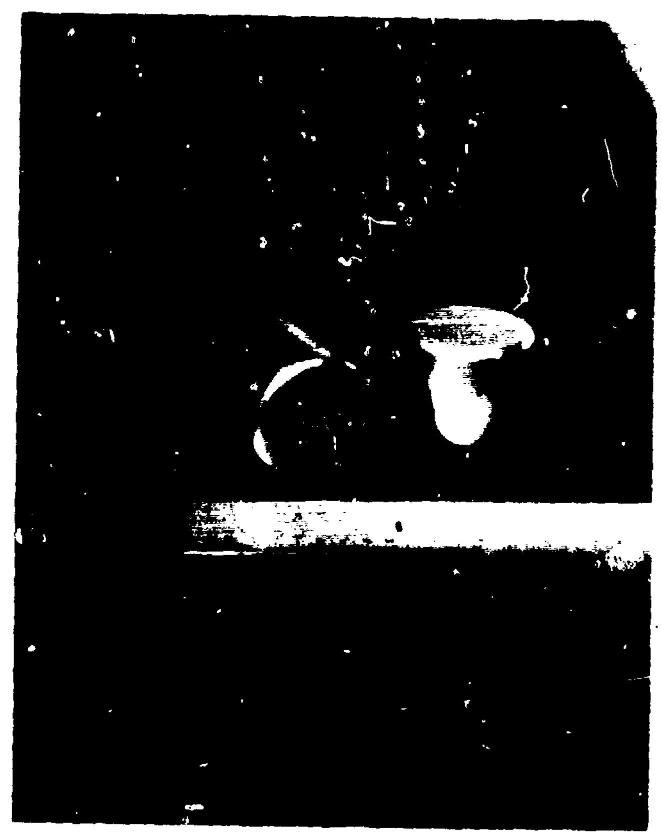


Figure 2.3. Rollers from the No. 4 Main Shaft Bearing of the F-100 Engine

cycle, carefully set into another container with respect to its being an acceptable or rejectable part.

The roller diameter is measured using an electronic amplifier, analog readout, comparator stand gauging unit. The roller is hand positioned on an anvil against an angled back stop, so positioned that the maximum diameter will repeatedly fall under the gauge head contact point. Once properly positioned, the roller is rotated by hand. During the rotation, the maximum diameter is noted, which is the required dimension, and the amount of out-of-roundness is observed for possible discrepancies. Once the maximum size has been established, the roller is placed in the proper container with respect to allowable sorting variations.

The roller length is also measured using an electronic amplifier, analog readout, comparator stand gauging unit. The roller is hand positioned on a serrated anvil under the gauge head contact point and randomly moved about to find the maximum length. Once the maximum length has been established, the roller is placed in the proper container with respect to allowable sorting variations.

End runout is measured on a special gauge designed to measure end runout and corner runout. The gauge is basically a V-block with a belt-drive system, a positive stop and a spring loaded locator utilizing two LVDT's located at specific gauge points for measurements. A roller is placed in the V-block against the positive stop and belt drive unit is brought into the drive position by pulling forward and down on a hand operated lever. The belt drive is then in proper position for driving the roller and provides the needed pressure to seat the roller into the gauge block. A minimum of three complete revolutions of the roller is required for each measurement cycle. The end runout is read from an analog meter as the total amount of needle movement during a single roller rotation. The drive unit is then raised and the roller is removed and turned end for end to measure the end runout of the other end.

Crown drop of a roller is measured on a three point OD type gauge. The roller, resting on its end, is placed between the two opposing gauge points and against a third gauge point which acts as a positive stop. After this initial step, the gauge amplifier is zeroed on the scale best suited for the tolerance range required. Next, the roller is removed from its position and placed between the gauge points against the positive stop, but raised to a gauge point predetermined and controlled by a riser block of specific thickness. The reading on the electronic amplifier with the roller in the raised position is equal to the amount of diametrical crown drop. The crown drop of the opposite end of the roller is measured by turning the roller over end for end, placing it on the riser block and remeasuring the roller mid-point.

Crown runout is measured on a V-block type gauge by placing the roller into the "V" with one end of it against a positive stop, preset for gauge point control. The roller is then resting in a V-block in contact with two LVDT's located at preset gauging points. A weighted belt drive unit is then brought into the drive position by pulling forward and down on a hand operated lever. The belt drive is then in proper position for driving the roller and provides the needed pressure to seat the roller into the gauge block. A minimum of three complete revolutions of the roller are required for each measurement cycle. The crown runout is then read from an analog meter as the total amount of needle movement during a single roller rotation. The drive unit is then raised and the roller is removed and turned end for end to measure the crown runout of the other end in the same manner.

Corner breakout is measured on an optical comparator by placing a roller against a preset stop, so positioned as to provide alignment of the roller end and crown intersection points with the grid lines on the comparator screen. The required dimensions are read from the image cast on a screen having a .001 division per graduation scale at 50 magnification. The breakout point(s) is considered as the point of angular break onto the flat planes of the end and/or the slightly rounded crown. The roller is picked up, turned over, and replaced against the preset stop in order to obtain the breakout point(s) of the opposite end. Due to variation in roller size (OD and/or length), slight comparator table adjustments are occasionally required.

Corner runout is measured on a special gauge designed to measure end runout and corner runout. The sequence of operations is the same as that described under the end runout operation. Generally corner runout is measured simultaneously with the end runout but requires an additional analog meter.

Flat length is measured by placing a roller in a V-block, tilt table type fixture, against a preset stop and moving a trigger type contact probe onto the roller surface. Through careful adjustment, the individual roller is leveled and maintained in a measurable position on the electronic amplifier analog scale, which is the readout device for the contact probe. Once leveled, a strip chart recorder is activated and the transverse table, on which the V-block fixture is mounted, is switched on and a profile trace is made. From this profile trace, the flat length is measured, utilizing a clear plastic scale. The scale is placed parallel to the strip chart horizontal lines in a best fit position to the profile trace and the intersection points of the trace and scale are marked. The distance between the marks is then measured for the flat length dimension.

Flat centrality of a roller is measured with the same equipment and care as used for flat length measuring, except for the addition of a sharp cornered block equal in height to the roller OD and located at the preset stop point. With this addition, the profile trace of the roller is started at the top of the added gauge block, allowing the gauge contact probe to traverse the block, drop off the sharp corner, and pick up the roller profile. Having achieved this, the strip chart is read for flat length, then divided at the mid-point of the flat length and measured back to the gauge block corner displayed on the profile trace. The difference between one half the roller length and the measured distance from the gauge block to the flat trace center establishes the dimension of flat centrality.

2.3 Alternative Measurement Approaches

Several alternative approaches for performing precision measurements of rollers have been considered. Each of the measuring techniques fit into one or more of four broad classifications for noncontacting measurements. These classifications are: full field, aggregated field, line reference and point reference. Full field systems perform measurements over the entire test volume, data being obtained independently for every point. An optical device which provides an image of a scene is a full field system. Aggregated field systems integrate the measurement over a selected area. A light meter which measures the average light reflected from a scene is an aggregated field system. Caution must be exercised to insure that the area measured is well defined so that the data will be meaningful. Line reference systems measure along one dimension, i.e., a line. A scanned line reference system becomes a full field system. A point reference system measures only one point of the field, generally, the distance from a point on the roller to a reference point. Most of the proximity probes considered in this study are point reference systems. It must be pointed out that all point reference systems actually integrate over a small but finite area. They, therefore, can be considered to be focused aggregated field systems.

The method by which the measurement is made has a direct bearing on the accuracy achieved. Consider the measurement of a single characteristic such as the diameter of the roller. The diameter measurement might be attempted directly by measuring across the roller as would be done using a precision micrometer. From Table II, it is seen that this would require a resolution of one part in 63,000, an accuracy which cannot be achieved by conventional instruments and procedures. A second approach is to make a differential measurement using a known reference block (or roller) with which a comparison is made. Only the difference in the dimensions between the reference and the roller is measured. Using a reference sufficiently close to the roller size allows use of a measuring device having a relatively low accuracy.

For instance, if a 0.623000" block were used for the reference measurement for the diameter, an accuracy of only one part in one hundred would be required to meet the 10 microinches tolerance. A differential measurement of this type requires that the measurement probe be positioned precisely the same with respect to the positions of the reference block and the roller. If the probe is fixed, then each roller must be precisely positioned in the same fixture. The accuracy of the measurement is only as good as the accuracy of the placement of the roller.

The problem of positioning the roller during the measurement is as difficult as the measurement itself. It is imperative that the position of the roller in the mount be totally predictable or it becomes necessary to locate the position of the roller prior to the measurement. A V-block fixture of the type commonly used for precision measurements tends to give false roundness readings for objects having an even number of lobes. Figure 2.4 shows a couple of extreme examples of this (Reference 1). Furthermore, the roller contacts the V-block at high points along the contact line. The locations of these points are unknown. The diameters of the rollers are centerless ground; a technique which tends to produce an odd number of lobes. However, some of the characteristics (such as corner and crown) are end ground, and this technique tends to produce an even number of lobes. If the

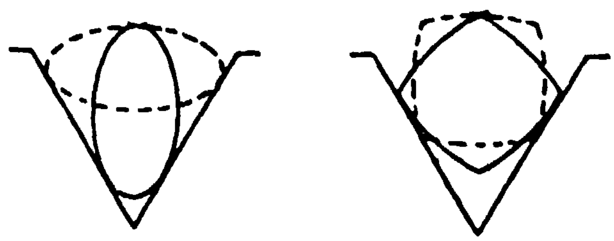
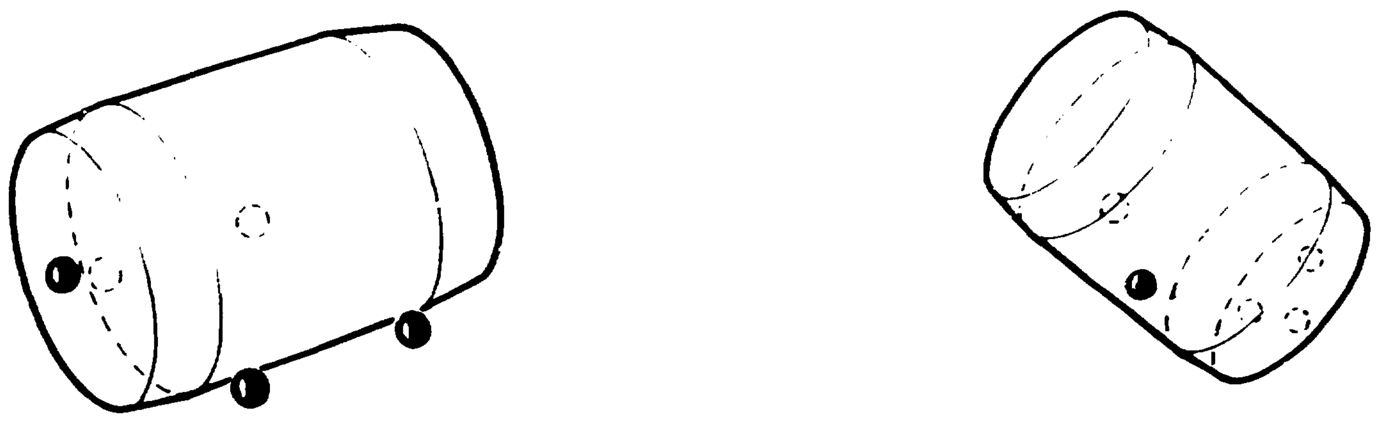


Figure 2.4. Even-Lobed Objects in a 60° V-Block

position of the roller in the fixture is not predictable, there can be no assurance that a true measurement of a characteristic such as the diameter is being made. The diameter is the length of a chord which passes through the center of the roller. Precise fixturing is required in order to locate this chord.

In order to precisely locate the roller, the mounting fixture must support it in five degrees of freedom; three translational and two rotational, since the roller is axisymmetric. The ideal fixture for accomplishing this, a kinematic mount, supports the roller at just five points. The locations of these points are chosen to complement the roller characteristics and the measurement tolerances. The contact points serve as the reference points for the measurements. Since the tightest tolerance is placed on the diameter of the cylindrical flat section of the roller, this area is the natural choice for the contact points. Figure 2.5a shows the positions of the five points of the kinematic mount; two located on either side along the flat and one at the end. A roller can be repositioned in this mount to within one microinch repeatedly. It should be noted that, although the contact points are fixed, the actual position of the roller is a function of its diameter. The procedure for calculating this position is presented in Section 5.1.1. An alternative arrangement is shown in Figure 2.5b where the mount has been reconfigured so that the end of the roller serves as the reference plane. This configuration may be advantageous for performing the Group II measurements.



a) b)

Figure 2.5. Roller positioned in a 5-point kinematic mount using a) the cylindrical flat as the reference and b) using the end as the reference.

3.0 SURVEY OF THE STATE-OF-THE-ART IN PRECISION MEASUREMENTS

A comprehensive survey was undertaken to identify noncontacting measurement techniques which can reliably measure tolerances in the range of millionths of an inch. This survey ranged from standard techniques such as air gauging to newer non-traditional methods such as holographic interferometry. Effort was made to seek out manufacturers which have devices available "off-the-shelf" for performing the required measuring function as well as manufacturers having the capability to produce a "special" device by modification of one of their standard products. In addition, various new techniques which are still undergoing development were considered.

3.1 Survey of Manufacturers of Measurement Devices

An important objective of the survey was to seek out any new or non-conventional measuring techniques which might otherwise have been overlooked for the roller inspection application. In addition, capabilities of conventional techniques were collected in order to determine whether they had the potential to be adapted to this problem. It was determined that the high precision dial indicator and LVDT (Linear Variable Differential Transformer) type measurement systems which are typical of the current inspection techniques used by roller manufacturers would be taken as a baseline of performance for this survey. Emphasis was placed on finding non-contacting measuring techniques which could meet or exceed the capabilities of these presently used techniques. Because of the nature of the problem, the survey concentrated in particular on various types of noncontacting position or displacement sensors.

Indices of product directories were searched for sources of measurement devices. This search yielded a list of over two hundred potential vendors. In order to reach this large number of vendors, a letter of inquiry was prepared which briefly stated the measuring problem being considered and asked for technical information on any device which might meet this requirement. The technical requirements stated were kept broad so that manufacturers producing marginally acceptable products would respond. In this way, the final determination of the usefulness of a technique could be deferred to the evaluation phase of this program. In addition to these letter contacts, other vendors which were known suppliers of measurement devices were contacted directly by telephone. A list of the companies which received the letters of inquiry or were contacted by other means are listed in the Appendix.

The mailer yielded responses from about 115 companies. Approximately one-half of these respondants stated that they could contribute to the solution of this problem. These responses were categorized as they were received to segregate those which appeared most promising. Some of the proposals were obviously not suited to this application. A number were for contacting LVDT-type devices which, although not of primary interest, helped to establish the state of this technology. Several of the responses detailed various types of linear and rotary encoders. While these devices are inappropriate for noncontacting measurement, their use will likely be required to monitor some of the peripheral control and manipulation functions of the inspection system. Finally, many of the responses did propose what appeared to be workable approaches for noncontact measurement of rollers.

The initial contacts produced a list of approximately thirty devices which met the basic requirement for high resolution, noncontacting measurements. Follow-up contacts with the manufacturers of these devices were made where possible in order to obtain more detailed technical information pursuant to the ability of their products to meet the tight specifications required for this program. Descriptions of the various types of devices encountered in this survey are presented in the next section.

3.2 Results of the Survey

The survey yielded measurement techniques which fall into three general categories based upon their principles of operation: electromagnetic, pneumatic and optical. The devices which fall within each of these categories can be further segregated into subclassifications as shown in Table III. Brief descriptions of the operating principles for each of these types of devices are given in the following paragraphs.

The devices which employ electromagnetic phenomena for measurement are of essentially three types: inductive, capacitive and Hall effect transducers. The inductive devices consist generally of small probes containing a coil near the tip. The coil is excited at a high frequency producing a magnetic field in the vicinity of the probe tip. Eddy currents are produced on the surface of a metal target within this field, thus producing a secondary field which alters the magnetic field produced by the probe. This change is detected as a change in the probe impedance which can be measured electronically. The eddy currents produced in the target are a function of its distance from the probe tip. Several manufacturers market variations of this device claiming resolutions on the order of a few microinches or less.

There are two types of capacitive devices which are used for proximity measurements. The first is essentially a plate capacitor where the probe serves as one plate and the target as the other. The capacitance is inversely proportional to the distance between the probe and the target. The second type of capacitive device integrates both "plates" of the capacitor within the probe tip. An electric field is produced in the vicinity of the probe tip which is altered by the presence of a metal target. In this case, the conductive target acts as a reflective "ground" plane. Both of these types of devices are driven at a high frequency and the change in capacitance is detected electronically.

A third type of capacitance device has been identified by TRW DSSG. This is a very sensitive aggregated field measuring technique which employs an extremely reentrant cavity resonator driven into oscillation by a tunnel diode. The roller rests on a kinematic mount which

TABLE III

CLASSIFICATION OF MEASUREMENT TECHNIQUES

- ELECTRO-MAGNETIC
  - INDUCTIVE
  - CAPACITIVE
  - HALL EFFECT
- PNEUMATIC
  - FLOW PRESSURE
  - BERNOULLI EFFECT
- OPTICAL
  - IMAGING
  - ATTENUATION
  - INTERFEROMETRY
  - DIFFRACTION

is positioned on the top of the cavity. The cavity is slotted in this area to permit the roller underside to protrude into the resonant cavity in close proximity to the reentrant post, as shown in Figure 3.1. Changes in roller diameter alter the post to roller spacing, in turn altering the cavity's resonant frequency which is electronically measured. A 3" diameter by 2" high sensor has been built (Reference 2) with a displacement measuring capability of a fraction of a microinch. It is reasonable to expect that a device could be developed using this technique with the capability to measure the various roller characteristics to an accuracy of better than 0.1 microinch. However, further analysis and experimentation is required before this technique could be deployed in a production environment.

A relatively new class of proximity transducers have been developed which are based upon application of the Hall effect. If current is flowing through a thin rectangular conductor (or semiconductor) in the presence of a magnetic field, then a voltage difference will be induced across the conductor transverse to the direction of the current. The induced voltage is proportional to the current and to the flux density of the magnetic field which is perpendicular to the conductor. Although this effect was demonstrated almost one hundred years ago, it has been the recent development of semiconductor and integrated circuit technology which has made its applicat[illegible]actical for proximity measurements. Several manufacturers market Hall effect sensors which are packaged on small microcircuit "chips". These devices are powered from a constant current source so that the output will be a function solely of the magnetic field which is present. In order to function as a proximity sensor, an external magnetic field must be applied. This field is altered by the presence of a metal target in the vicinity of the sensor. The device can be configured to produce a voltage which is a function of the distance between the sensor and the target.

Pneumatic techniques have long been recognized for their ability to reliably make precision measurements. These devices operate by discharging air through an orifice at a carefully regulated pressure. The

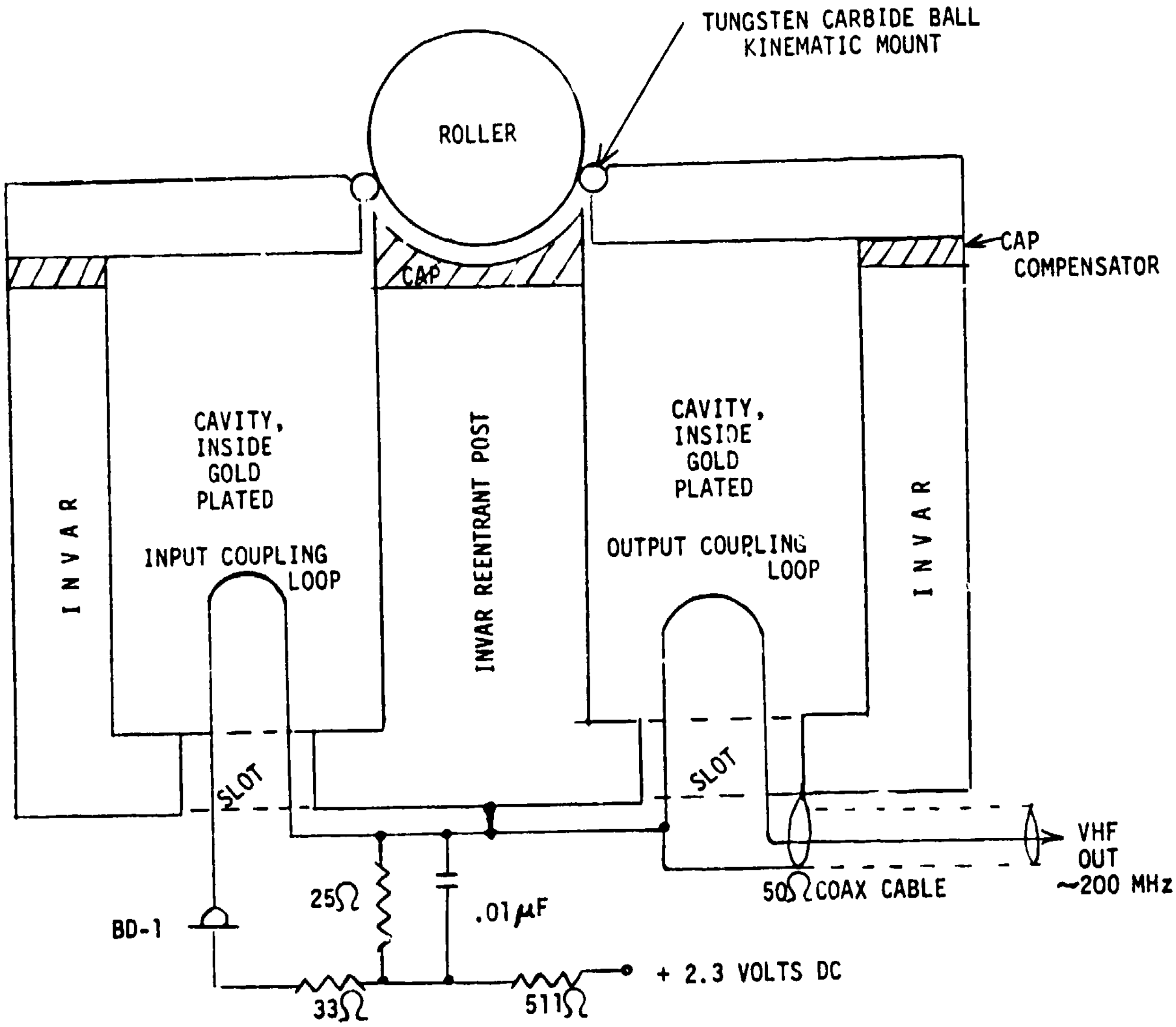


Figure 3.1. Extremely Reentrant Cavity Resonator Position Transducer

flow of air then impinges upon the target. The presence of the target modifies the air flow in a manner which is proportional to its distance from the orifice. This change, and consequently the separation between the air orifice and the target, can be measured in two different ways. The first technique is to measure the back pressure in the air stream due to the presence of the target. The target serves to restrict the flow thus producing a change in the air pressure in the flow behind the orifice. The electrical analogy of this effect is that the "load" produced by the target changes the "impedance" of the output orifice. The change in pressure is similar to a change in voltage in a circuit whose output impedance is altered. An alternative technique for measuring the location of a target near the orifice is to employ the Bernoulli effect. The flow of air from the orifice produces a corresponding drop in the air pressure in the vicinity of the flow. One device which employs this technique has an orifice in the shape of an annulus with a small pressure transducer at the center of the annulus. The pressure detected by this transducer can be related directly to the location of the target in the air flow.

The optical solutions to the problem of precision measurement are not as readily defined as the electromagnetic and pneumatic techniques described above. Whereas the electromagnetic and pneumatic techniques correspond for the most part to specific products which can be used with little or no adaptation, the optical techniques relate to concepts which must be configured for the particular application being considered. For convenience, the optical techniques are classed into four groups, although some techniques may rightfully belong in more than one group. These groups correspond to the optical phenomena used in measurement: imaging, attenuation, interferometry and diffraction.

The optical imaging techniques consist of many diverse methods in which an image of all or part of the roller is obtained and subsequently measured or otherwise analyzed. There are five parts of an image analysis type system, each of which can be considered separately. These parts are: illumination, orientation of the target and other fixtures, imaging optics, photodetector, and electronic analysis. A number of approaches were identified for each of these system parts. In general, these can be intermixed to arrive at the most suitable final measurement concept.

The choice for illumination resolves to decisions on whether to use monochromatic or white, coherent or incoherent light and whether it should be collimated, a "point" source, or focused onto the target. There are advantages and disadvantages to be weighed in making each of these choices. The interfacing with the other elements of the imaging system must also be considered.

The target can be oriented with respect to the illumination so that its surface is illuminated or it can be back-lighted so that its edge is well defined. In this latter configuration, another object such as a knife edge, may be placed in juxtaposition with the target so that their relative positions can be compared.

The imaging optics must have a field of view which is sufficient to cover the total range of the portion of the roller being measured with a resolution suitable for the tolerance required. A number of image processing lenses have been identified which are suitable for the roller measurement application. There are also some approaches where the imaging lens is not used. In these cases, the illumination optics are used to project an image directly into the photodetector.

The technique for converting the optical image into electrical signals is the heart of an imaging measurement device. One technique is to use a photodetector tube such as a vidicon or an image-orthicon. These are tubes which are commonly used in television cameras. The light sensitive face of the tube is scanned with an electron beam to yield an electronic representation of the two-dimensional image. The location of an object within the image is determined by analyzing the data to identify the object while simultaneously determining the position of the scanning beam. An alternative technique is to use photodiodes, either singly, or in a one- or two-dimensional array. A photodiode is a solid-state detector which can be made very small. A two-dimensional image can be recorded by a single point detector by employing scanning mirrors to move the image across the detector. A better approach is to use a one-dimensional photodiode array, which if properly oriented, can be used to locate the edge of an object without scanning. If the entire image needs to be recorded, then scanning in only one dimension is required. These arrays typically consist of diodes measuring approximately 0.0005" square and they may have from one hundred to over two thousand diodes. At least two manufacturers have standard one-dimensional arrays containing 1728 diodes in an array less than one inch long. The resolution obtainable with this device (i.e., one part in 1728) exceeds that from a television type system. Furthermore, the location of each element of the array is fixed whereas locations determined with tube systems are subject to drifts in the controlling voltages of the tube. Two-dimensional arrays are also available, however, the largest ones currently marketed have only 256 by 256 elements. This may be adequate for the lower accuracy measurements such as for the corner breakout, but does not have the resolution required for the diameter or length measurement.

Once the image has been converted into electronic information, this data must be analyzed to verify the tolerance of the measurement. This task can be performed by instruments that range from simple timing devices which are synchronized to the detector scan to sophisticated hard-wired image analysis computers. In practice, when the measurements are divided into the subgroups outlined in Table I, the data manipulation required to determine each roller characteristic is quite straightforward. A number of small microcomputers are available which can readily handle this data analysis task while at the same time providing control over the entire operation of the inspection system. Some of these small computer systems are designed specifically for handling this type of problem while other smaller systems can be programmed for this application.

As noted, there are numerous variations for applying image analysis to measurements of roller characteristics. Many manufacturers have proposed systems employing combinations of the techniques discussed.

The problem is to select the most desirable technique for each measurement, and to integrate them into a working system.

The optical attenuation techniques are proximity measurements, similar to electromagnetic probes in application. The more developed devices of this type employ fiber optic bundles to transmit light onto the surface of the roller and to receive the light which has been reflected from it. Fibers are arranged within the same bundle to serve as either transmitters or receivers. A photodetector is used to monitor the amplitude of the reflected light. The device is calibrated so that the proximity of the roller to the probe can be determined from the analog signal from the photodetector.

Optical interferometry measurement techniques employ the property of coherent light which produces interference fringes when a beam is split and the two parts of it are subsequently intermixed. The recent development of the laser as an inexpensive source of monochromatic, coherent light has made possible the application of interferometric techniques where, before, they were not practical. Traditional interferometers, such as a Michelson interferometer, are generally limited to use with flat, specular surfaces where they can measure tilt and flatness with extreme precision. A newer technique, holographic interferometry, is applicable for inspecting objects which have non-flat, diffuse surfaces. For measurement of rollers, holographic interferometry is applied by making a master hologram of a "standard" roller and then comparing other rollers to it. This is a full field technique which measures the entire visible surface of the roller simultaneously. The interference fringes which appear on the tested roller correspond to the differences in size between it and the "standard" roller. It is a very sensitive technique; the first fringe formed corresponds to a size difference of approximately six microinches. It is necessary to use a two-dimensional photodetector (either a tube or scanned array) so that the entire image can be analyzed using a computer in order to determine the location of the interference fringes. Holographic inspection techniques are just beginning to find their way into industrial applications. The state of this technology is developed to the point where it could be readily applied to the roller inspection problem.

Optical diffraction techniques measure the change in monochromatic laser light as it passes near the roller rather than the effect of its reflection as in interferometry. The light passes between the roller edge and a knife edge which is positioned close by. The "slit" diffraction pattern is detected by either a one- or two-dimensional photodetector (such as those discussed above) and subsequently analyzed by a microcomputer. The distance between the roller and the knife edge (which must be in a known position) can be calculated for every point along them using classical optical diffraction equations.

4.0 EVALUATION OF MEASUREMENT TECHNIQUES

The survey of precision measurement techniques yielded approximately thirty devices from several different technology areas which met the basic criteria for use in roller inspection. In order to render this list to determine the most appropriate techniques, it is necessary to establish standards for their evaluation. Using these as a basis, the individual devices can then be fairly evaluated.

4.1 Basis for the Evaluation

There are three sets of criteria upon which a candidate measuring technique must be evaluated. These are measurement characteristics, performance characteristics and cost. Measurement characteristics refer to what is actually measured and how it is done. Performance characteristics refer to how well the technique accomplishes this task. For some techniques, development costs must be considered in addition to acquisition and operating costs.

Most of the techniques evaluated consist of some form of position or proximity sensor. While many of these devices function as point probes, they actually measure over a finite surface area. Because the roller surface is not flat, this area must be small if errors are to be minimized. The manner in which the measurement is integrated over this area must also be considered. In general, the electromagnetic probes provide an approximately arithmetic average of a measurement over a curved surface which can be readily reduced to yield the required measurement. The pneumatic probes, however, produce an output which is highly dependent upon the surface curvature, thus making the results harder to interpret. The interaction of the sensing field (electromagnetic, optical, etc.) with the roller material must also be considered. For example, some techniques are dependent on the electrical characteristics, such as conductivity and permeability, of the rollers. These and other similar factors must be weighed in order to determine the applicability of a given technique to the measurement of a particular roller characteristic.

It is then necessary to consider the performance characteristics of the candidate measuring technique. The following set of eight parameters have been defined as the basis for comparing performance. The order in which they are presented corresponds roughly with their order of importance.

- Repeatability - This is a measure of the device's ability to produce the same result consistently. The device must provide a stable output which is free of random drift. In practice, this means that if an individual roller were to be measured repeatedly, the result would always be the same.

- Resolution - This is the precision of the measurement. The required precision for the various roller characteristics corresponds to the tolerances given in Table I. The limiting factor of the resolution is the noise which is present in any measuring device. Where the measurement is repeatable, however, a large number of repetitions can statistically improve the signal-to-noise ratio, and consequently the resolution of the measurement.

- Sensitivity to surface finish - The dimensional measurements must be independent of small variations or blemishes in the surface finish which are otherwise acceptable. The optical techniques are likely to be more susceptible to this kind of error.

- Temperature dependence - Most measurement techniques have some degree of temperature dependence. This factor must be known (and be repeatable) so that either the temperature can be controlled to the required stability or the temperature-produced error can be compensated for in the calibration of the instrument.

- Environmental sensitivity - In addition to temperature dependence, other environmental factors such as dust, humidity and vibration may affect the performance of the measurement device. The extent to which the instrument compensates for or is otherwise shielded from these factors must be established in order to determine its capability for operating in a manufacturing or maintenance environment.

- Data presentation format - In order to automate the roller inspection, it is expected that a microcomputer will be required to receive and analyze the measurement data. The format of the data must, therefore, be compatible with a computer interface. Most electro-magnetic type sensors produce either an analog or digital output which is proportional to the measurement. Optical imaging systems often present data in a "visual" format which can be difficult for a microcomputer to interpret.

- Overall accuracy - This is the absolute calibration of the device as compared to a standard. Although it is convenient to use a device which indicates the correct measure, any device which is repeatable can be calibrated to perform the measurement function.

- Linearity - As with accuracy, it is convenient to use a device having an output which is linear with respect to the measurement. However, non-linearities are readily taken into account in the calibration of the instrument.

The above parameters all relate to the ability of a device to adequately perform the measurement task. In addition, there is the requirement that the device be reliable. It must be able to function properly on a regular basis in a manufacturing environment. Maintenance requirements must be minimal so that downtime will not interrupt work schedules.

There are several costs to be considered for each inspection technique. Some of the devices are not fully developed to the point where they are ready for inclusion into an inspection system. The required development may range from fixturing and electronic interfacing problems to full scale research programs to establish capabilities of new techniques. Devices which fall into the latter category have not been seriously considered here because the high cost and long lead times may not be justified by this problem. Acquisition costs become a significant factor when comparing point vs. field techniques. For instance, proximity probes are generally much cheaper than optical devices. However, one set of optics may be able to replace an entire array of probes. Finally, it is not expected that operating costs will be a significant factor for any of the devices under consideration.

4.2 Results of the Evaluation

The measurement techniques described in Section 3.2 were evaluated to determine the feasibility of their incorporation into a roller inspection system. Data for this analysis was obtained from the manufacturers of the various devices and from an independent study of the underlying physical basis for each measurement. Specifications supplied by manufacturers were checked where possible with other sources familiar with the use of these devices. Unfortunately, it was only possible to obtain a few of these devices for inspection and then only a cursory examination was possible. Nevertheless, sufficient data was collected to allow those techniques with high probabilities of successful application to be segregated from those of doubtful applicability. Final selection of techniques to be incorporated into a prototype inspection system will require direct comparison testing under simulated operating environments to be performed in a follow-on to this study.

Inductance and capacitance proximity probes reside in technology areas that have been used in industry for many years, yet are still undergoing refinement as they continue to incorporate new technology in materials, structural design and electronics. It is interesting that while these two devices employ different physical phenomena as their basis for measurement, they have very similar methods of deployment, operating characteristics and even physical appearance. Both of these devices provide a measurement of the distance between the target and the probe which is approximately an arithmetical average integrated over the area of the probe tip. Typical probes of both types have tip diameters of approximately 0.062 inches, though one of the integrated capacitance probes studied has a tip only 0.019 inch in diameter. This compares favorably with currently used contacting LVDT-type probe tips having 0.030 inch diameters. Contacting probes read the high points rather than averaging the measurement. Figure 4.1 shows the general configuration of these probes. In both cases, a high frequency (> 1 MHz) oscillator is coupled through a bridge circuit to the coil or capacitor sensor. The proximity of the target is detected as a change in voltage across the bridge due to the change in impedance at the sensor. Resolution is a function of the electronic noise present. At least one inductive and one capacitance device have incorporated dummy loads as well as all or part of the bridge-oscillator circuitry into the probe itself. This reduces the noise level and minimizes sensitivity to changes in temperature. These devices are capable of resolving less than one microinch over ranges of up to 0.020 inch.

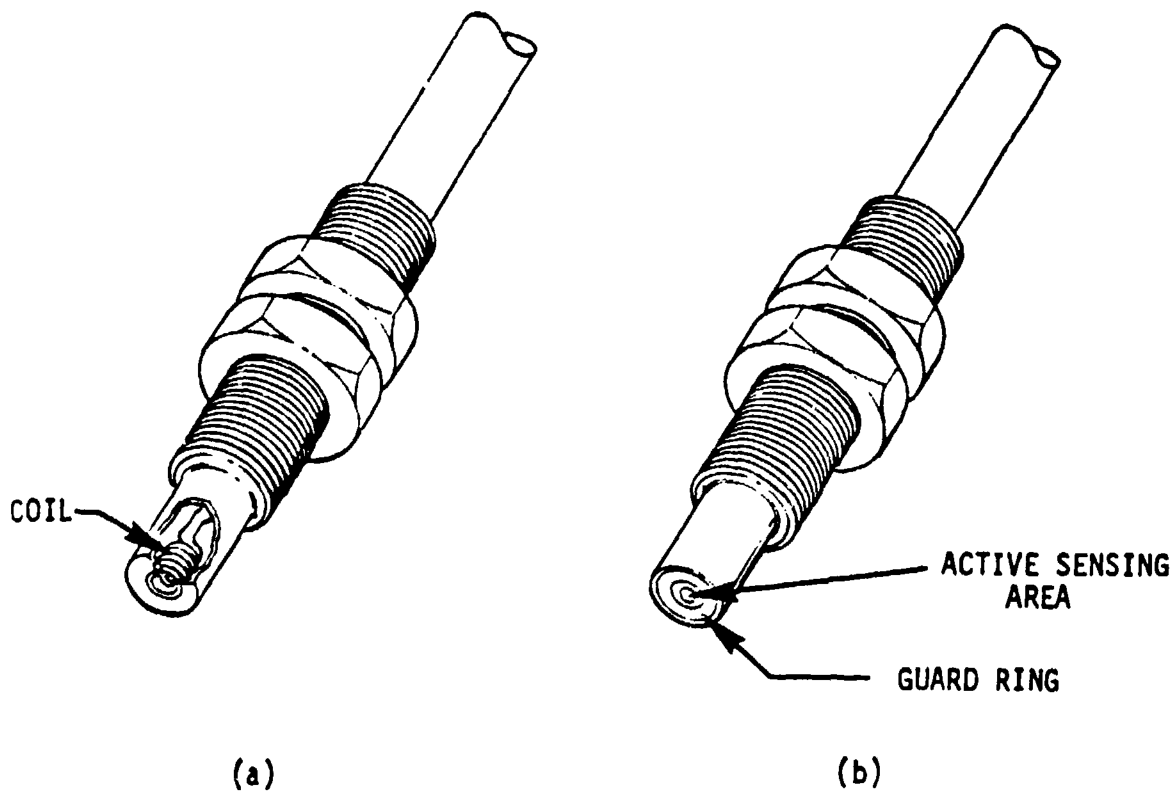


Figure 4.1. Inductance (a) and Capacitance (b) Probes.

Either type of probe appears capable of serving as a noncontacting substitute for the LVDT devices presently in use. The inductance probes are sensitive to differences in the permeability of the roller material. This might cause errors due to slight superficial inhomogeneities in the material properties or differences in the surface hardness between rollers. On the other hand, these devices are less sensitive to dust and other contaminants than the capacitance probes. A thin film of oil on the roller could cause an error in the capacitance measurement, though not in the inductance measurement. It is also possible that changes in humidity may cause an error in this measurement. It is doubtful that any of these factors will be significant in light of the care which must be taken to provide a clean, stable environment for the inspection process. However, it will be necessary for laboratory tests to be performed to directly compare performance characteristics before a final selection could be made between an inductance and a capacitance proximity probe.

The aggregated field capacitance technique which uses an extremely reentrant cavity resonator is the most sensitive measuring technique identified in this survey. The fact that the measurement is integrated over a relatively large area of the roller's surface can make it difficult to interpret the data. This problem can be minimized by careful selection of the area surveyed. The sensing area can be reduced to an area comparable to that of a point proximity probe. This reduction in measuring area produces a corresponding reduction in sensitivity. Nevertheless, even a 0.019" diameter area (the smallest of any standard electromagnetic probe) provides a resolution which is several orders of magnitude higher than any other known capacitance or inductance probe. This technique is also one of the least developed of those evaluated. While its ultra high sensitivity justifies its serious consideration, a thorough laboratory evaluation is necessary before this technique could be utilized.

The Hall effect sensors appear to have the sensitivity of the inductance and capacitance proximity probes. However, they have not been developed to the same degree of sophistication. The packaging techniques which serve to minimize noise and environmental effects while permitting easy installation are not yet present in this class of devices. The operation of Hall effect sensors is also dependent on the presence of an externally produced magnetic field which must be unidirectional and stable for the device to remain calibrated. Solid state sensors are also inherently very temperature sensitive. This technology is still undergoing development and the use of these devices may be advantageous at a future time. For the present, however, the inductance and capacitance probes are better choices for this application.

Pneumatic flow pressure measuring techniques have been in widespread use for precision measurements in industrial applications for many years. Their capabilities are well established. These techniques can be used for determining geometrical relationships such as taper, parallelism and squareness as well as dimensions. The fixtures required, however, must be closely matched to the roller. The close clearances required complicate the movement of the roller in and out of the measuring stage. These air gauges are also configured as proximity probes which can be deployed in a manner similar to the electromagnetic type probes. Their sensitivity is on the order of a few microinches and is not subject to electromagnetic interference. It is possible that erroneous results may be obtained when measuring the curved surfaces of the rollers due to the nonuniform flow pattern produced. However, it is likely that these errors can be corrected in the calibration of the probes. The history of successful application of pneumatic probes for similar precision measurement problems makes them good candidates for this application.

The pneumatic probe which employs the Bernoulli effect is a relatively new development and the full extent of its capabilities is not known. The manufacturer of this device had made no attempt to verify its resolution to better than 0.005 inch. It would appear that the resolution of this device may be considerably better, however, laboratory testing is required to establish its performance characteristics.

Optical imaging measurement techniques have the advantage of providing data over a field of view which allows for an accurate characterization of the roller. On the other hand, these techniques produce copious amounts of data which must be sorted electronically in order to be useful. If the optical system is carefully designed to fit the specific application, then the data handling requirements are greatly simplified. It must be kept in mind that many of the measurements either approach or exceed the resolution capabilities of optical systems. The classical resolution of a "good" lens is more than the wavelength of the light used. Considering that the wavelength of light is on the order of 25 microinches, then the tolerances below 100 microinches are "pushing" the traditional capabilities of optical imaging systems. It remains necessary to employ electronic analysis and statistical analysis techniques in order to achieve the required resolutions. Using these techniques, resolutions on the order of a few microinches are indeed achievable.

The imaging techniques which are promising for this application are those in which the roller is backlighted, providing a silhouette of the edge. The diffraction effects due to the light passing over the rounded roller edge need to be considered in the calculations to reduce the data. The ideal illumination is monochromatic, noncoherent light. Monochromatic light is subject to less aberration caused by the processing lenses and the diffraction effects are much simpler than polychromatic light. The resolution of an image produced with noncoherent light is about 21% better than that produced with coherent light. (Reference 3.) Furthermore, the image of an incoherently illuminated edge exhibits a simple structure with no diffraction fringes (Reference 4). Lasers are inexpensive sources of monochromatic light, however, their outputs are generally coherent. There are some high order multimode lasers which may be suited for this application. Arc lamps are also available which produce noncoherent light which is very close to being monochromatic. A collimated illumination beam is easily produced and can help simplify the data analysis.

With the roller backlighted by a beam of collimated monochromatic light, the silhouette of its edge can be projected directly onto the photodetector. Because it is desirable to introduce a magnification factor before the photodetector, an imaging lens (or lenses) is needed. Designing a special lens for this application is prohibitively expensive, so an existing optical system should be adapted. There are two types of optical systems which are suitable. The first is a microscope type system utilizing a microscope objective lens as the primary optical element. These lenses have very short working distances (the longest are about one half inch) and small fields of view. The other type of standard lenses which are applicable here are processing lenses, either those designed for photolithography or those designed for microcircuit production. Lenses in this latter category have very high resolutions (near diffraction limited) and also large fields of view. One of these lenses could be used to process an image of the entire roller with adequate resolution for the most critical of the required measurements.

For this particular application, solid state photodiode arrays have several advantages over the tube type image sensors. The most significant of these is that the array is dimensionally stable. The location of a feature in the image is determined absolutely by the "address" of the array elements where it is detected. Linear arrays with over seventeen hundred elements (now available "off-the-shelf") provide a stable image resolution of one part in 1700. Multiple arrays can be employed serially to increase this effective resolution. The "address" locations from phototube detectors are determined by the control voltages on the tube. These are subject to drift, nonlinearities and interference from external electromagnetic fields. While these factors can be controlled through careful regulation and shielding, they are simply not present with solid state arrays. The arrays also require less support electronics and installation space and their outputs are already in a digital format which simplifies interfacing to a microcomputer.

The photodiode arrays which provide this high resolution are only available in a one-dimensional (linear) format. The largest two-dimensional arrays currently available have 256 by 256 elements. It is, therefore, likely that the image would have to be scanned across the linear array by using a rotating mirror or prism in the optical path. The mechanical position of the scanning mirror is subject to errors similar to the electronic drifts and nonlinearities of the phototube. However, the very nature of the roller measurement problem lends itself to such a system. A relatively high resolution is required to determine the location of the edge with respect to the roller's axis, i.e., the radial location of the edge. This can be done by positioning the photodiode array transverse to the roller axis so that its high resolution measures the radial component. The resolution needed to measure the axial location is over two orders of magnitude less. By using the mirror to scan the image across the array in the axial direction, the edge profile can be determined to well within the tolerance requirements of the problem. The analysis of the data outputed by such a system is very simple compared to that for the output of an imaging tube.

The optical attenuation-type proximity probes have excellent resolutions when used over a very short sensing range. A resolution of one microinch over a 0.005 inch range is typical. Within this range, the output vs. distance curve is extremely steep. The curve flattens out to $\sim 1/d^2$ for larger working distances (to over one tenth of an inch) but the resolution drops accordingly. These devices have the advantage of being able to employ a fiber optic bundle for the probe tip, which greatly simplifies the fixturing problems. All of the support optics and electronics can be located apart from the measuring stage. This offsets the problem encountered with using the short working distance in order to obtain the higher resolution. The main disadvantage with this technique is its sensitivity to slight variations in surface finish. The variation of surface reflectivities among rollers needs to be established in order to determine whether this technique will have the repeatability required for this application.

Optical interferometry techniques such as holography meet all of the basic requirements for roller inspection. They provide a complete characterization of the roller geometry, far more data than is actually needed to meet current inspection requirements. The cost of implementing these techniques for a manufacturing system is higher than for many of the other alternatives. The cost of the added data reduction cannot be justified if the data is not needed. At this time, it appears to be more cost effective to employ the simpler proximity probe and imaging techniques. It should be noted that the optical interferometry techniques are ideally suited for use in the laboratory experiments which are needed to establish the capabilities of the other measurement devices. Optical interferometry can also be used to align and calibrate the measurement stations of the completed roller inspection system.

The optical diffraction techniques suffer from several disadvantages. It is necessary to position a knife edge in close proximity to the edge being measured. While the technique is extremely sensitive, its range is very limited. The analysis of the diffraction pattern to determine the slit width is more difficult than simple image analysis. The technique is workable and can adequately measure the rollers, however, it does not appear to have any advantages over some of the other alternative techniques which are simpler to implement.

In addition to the measurement techniques discussed above, several electronic processing methods for enhancing system performance were identified. It was determined that the signal-to-noise ratio of most proximity probes can be improved by as much as 30 db using phase coherent modulation/demodulation techniques. This would result in a significant improvement in the resolving power of these probes. The spatial resolution can be similarly improved by using a deconvolution analysis. The capability of some of the optical techniques can be enhanced by additional image processing. The accuracy of an optical imaging measurement can be improved in some cases by multiplexing two images into a single image. Image shearing optics can improve the ability of the system to identify the location of an edge. In evaluating potential performance capabilities of measurement techniques, these and other similar enhancement methods would naturally be considered.

5.0 A CONCEPT FOR THE MEASUREMENT OF HIGH SPEED ROLLERS

A number of measuring techniques have been identified in the previous sections which meet the basic accuracy, repeatability and other requirements for roller inspection. The manner in which these devices can be employed to measure specific roller characteristics will now be considered. It will then be shown how these measuring techniques can be combined into a fully automated roller inspection system.

5.1 Measurement of Roller Characteristics

The thirteen roller characteristics which are of interest were listed in Table I where they were divided into six subgroups. Methods for measuring the characteristics in each of these groups are considered in the following paragraphs. In some cases, several alternative approaches are presented and compared.

5.1.1 Measurement of Diameter, OD Taper and Cylindricity

The characteristics listed under Group I (diameter, OD taper and cylindricity) are the most difficult to measure reliably because of the accuracy required. A full field measuring technique such as holographic interferometry would be ideal if only a single roller diameter were encountered. Rollers which matched the diameter of the master roller within the required 10 microinch tolerance would produce no interference fringes. Out-of-size rollers would produce one or more fringes. This "something or nothing" difference could be easily determined using an electronic image sensor. In fact, the roller diameters may range over several hundred microinches requiring that they be "sized" to within the 10 microinch tolerance. In principle, the complicated holographic fringe patterns produced in this situation could be recognized by an image analysis computer which could determine the roller diameters. In practice, however, this would require a large expenditure for acquisition and programming of the computer. The cost of this approach will probably exceed that of the other alternatives.

Optical imaging techniques have the desired features required for this measurement. A line measurement made along the edge of the roller would yield the diameter (and thus taper) along the entire flat part of the cylinder. One approach to accomplish this measurement is to directly image the roller onto a linear photodiode array and measure the shadow produced as shown in Figure 5.1. The required accuracy (1 part in 63,000 from Table II) can be reduced by employing an optical multiplexer, shown in Figure 5.2, to remove the center of the image. This device consists of a pair of rhombohedral prisms which combine the images of the two opposing sides of the roller into a single image. The result is a fixed reduction in the apparent size of the roller and a corresponding reduction in the required accuracy of the measurement. (Accuracy is defined as the dimension divided by the tolerance.) This imaging scheme, which always gives the measure of the maximum chord perpendicular to the direction of illumination, yields a result which is as close to a true diameter measurement as any contacting method. It also has the advantage of providing an absolute measurement requiring only the fixed magnification factors of the optical multiplexer and the imaging lens for calibration.

This same type of diameter measurement can be performed using two proximity probes which are diametrically opposed about the roller. Figure 5.3 shows two possible arrangements of probes. Probes in the "A" positions are preferred because the kinematic mount assures that the diameter is measured through the center of the roller. This arrangement, however, makes it difficult to move the roller in and out of the mount without moving the upper probe. Probes located in the "B" positions overcome this drawback, but add some uncertainty in that the center of the roller is displaced up or down with respect to the mount as a function of the diameter of the roller. This factor must either be considered in the measurement calculations or it can be removed by allowing the plane of the probes to be moved vertically so that the maximum chord can be determined. This displacement can be accomplished using a piezoelectric transducer to dither the location of the proximity probes to allow the maximum value to be recorded.

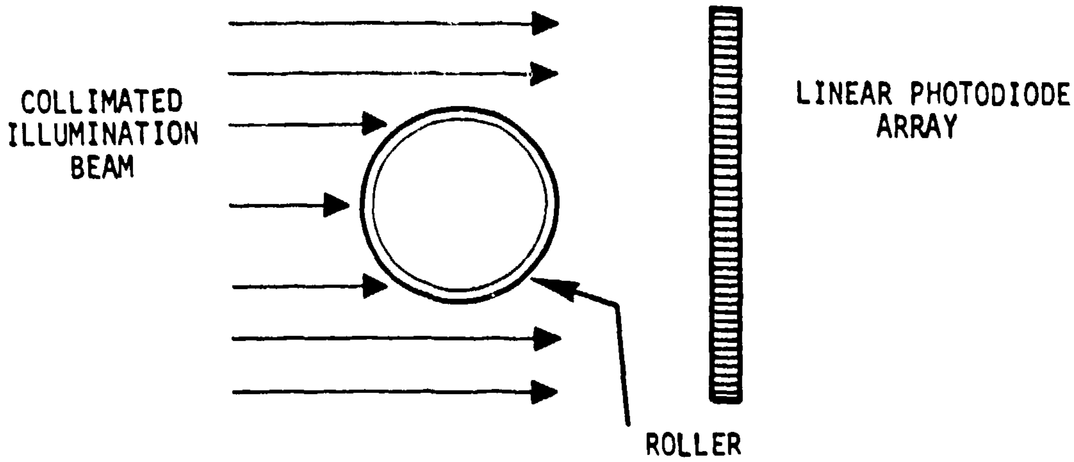


Figure 5.1. Measurement of Shadow of Roller in a Collimated Illumination Beam with a Linear Photodiode Array

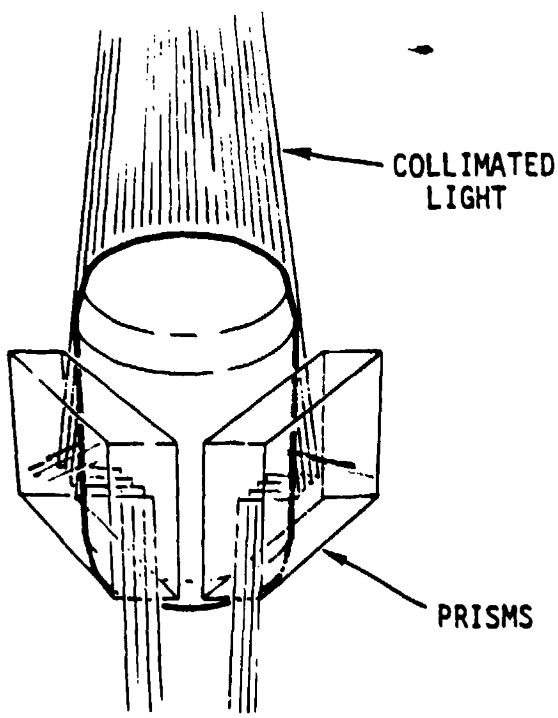


Figure 5.2. Optical Multiplexer Combines the Two Images of the Opposing Sides of the Roller into a Single Image

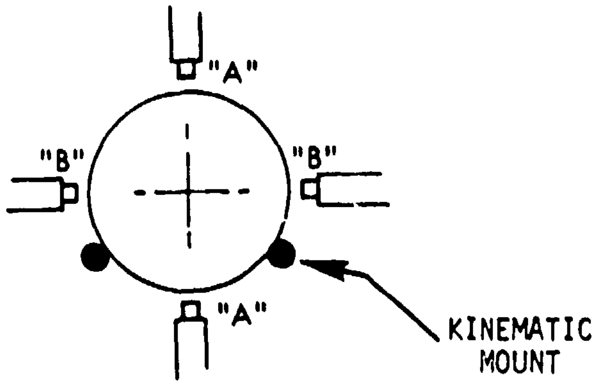


Figure 5.3. Two Possible Configurations of Proximity Probes for Measuring Roller Diameter

An alternative approach for measuring the roller diameter is to determine the position of some location of the roller's circumference with respect to the position of the kinematic mount. This is illustrated in Figure 5.4. This figure gives a cross-sectional view of a roller in a five point kinematic mount. The "height", y, of the top of the roller (point "A") above the line connecting the contact points between the roller and the mount is

$$y = d/2 \left(1 + (1-S^2)^{1/2}\right) \qquad (1)$$

$$S = x/d \text{ (note: } S \leq 1)$$

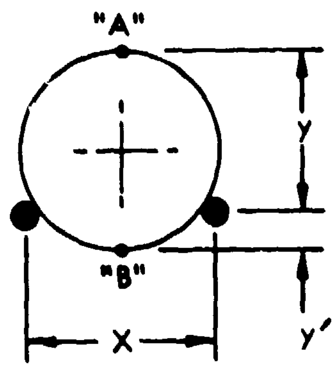
where

x = the distance between the two contact points

d = roller diameter.

The change in y as a function of a small change in the diameter is found by differentiating Equation 1.

$$\Delta y = \frac{1}{2}\left[1 + (1 - S^2)^{-1/2}\right] \Delta d \qquad (2)$$



$y + y' = d$

Figure 5.4. The Position of Points "A" and "B" with Respect to the Location of the Kinematic Mount Change as a Function of the Roller Diameter, d.

Similarly, the change in "height" of point "B" at the bottom of the roller for a small change in diameter is

$$\Delta y' = \frac{1}{2}\left[1 - (1 - S^2)^{-1/2}\right]\Delta d \qquad (3)$$

Figure 5.5 shows the ratios $\Delta y/\Delta d$ and $-\Delta y'/\Delta d$ as functions of S. The negative sign has been added here so that the magnitudes of these numbers can be readily compared. It is important to note that $\Delta y/\Delta d$ is greater than one for all values of S. This magnification factor serves to increase the sensitivity of the measurement. Although it is desirable to measure the diameter at the top of the roller, the problem of moving the roller in and out of its mount is again encountered. From the graph in Figure 5.5, it is seen that even $(-\Delta y'/\Delta d)$ is greater than one for sufficiently large values of S (e.g., for $S \geqslant 0.94$). From Equations 2 and 3, the difference between $\Delta y/\Delta d$ and $-\Delta y'/\Delta d$ remains constant at 1. While it is obviously desirable for S to be large in order to increase the magnification factor of the measurement, there is a practical limit imposed such that the mount will be able to support

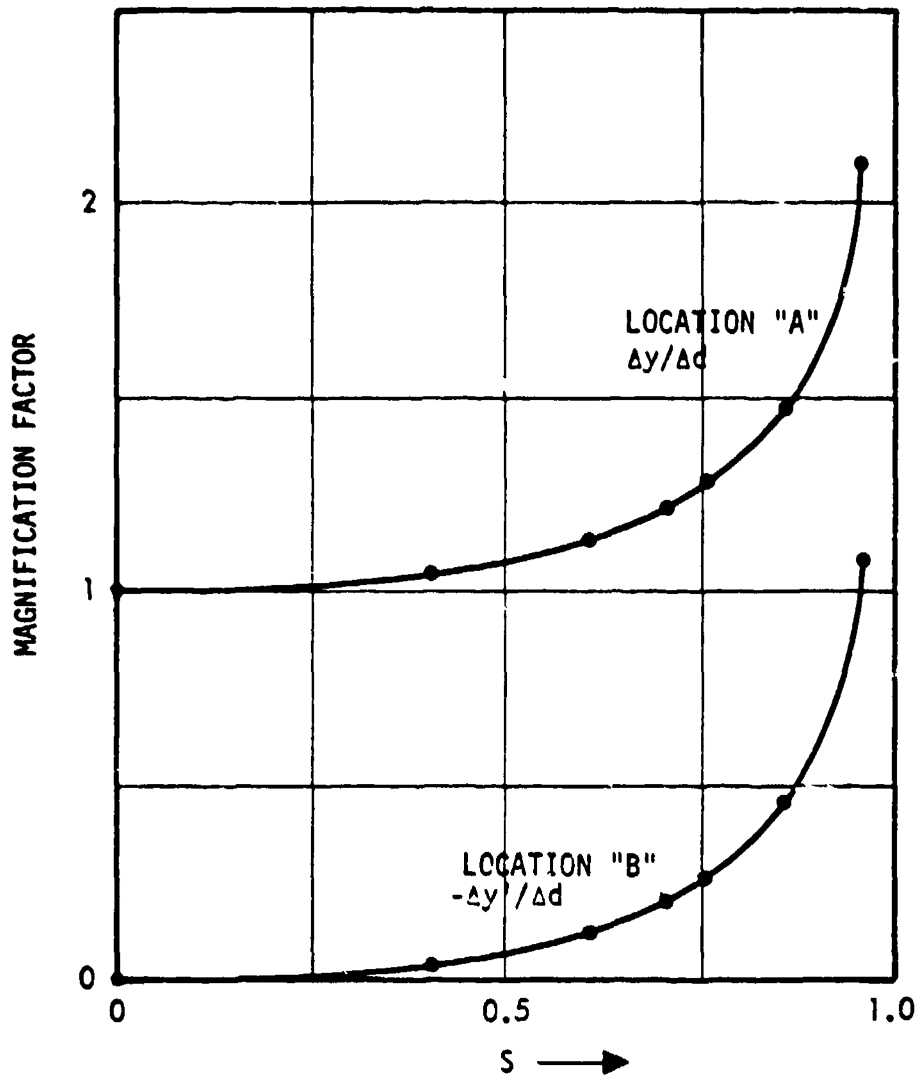


Figure 5.5. Magnification Factors for Locations "A" and "B" as a Function of the Ratio of Roller Diameter to Mount Spacing(s)

the load of the roller and be able to accept a range of roller sizes. It would seem that a practical upper limit on S would thus be approximately: $S < 0.990$. This corresponds to magnification factors of approximately 4 for measurements made at the top of the roller and 3 for measurements made at the bottom of the roller.

The actual measurement of the roller diameter using the "position" determining technique can be made with either point, proximity probes or by the optical techniques which have already been described. The optical techniques have the distinct advantage of requiring less space adjacent to the roller thus easing the problem of its manipulation. This "position" technique is more sensitive than the direct diameter measurement technique because of the magnification factor produced by the mount. The calculations for determining the diameter from the sensor output are more complicated but well within the capability of the microcomputer which is needed to control the entire operation. Any of the techniques described in this section could be employed to perform the diameter measurement.

The other measurements required in Group I (OD taper and cylindricity) follow directly once a measurement technique is chosen for the diameter. The OD taper is calculated from diameter measurements made at two points on the cylindrical flat. From these, the slope of the flat can be determined and consequently the maximum taper. The cylindricity measurement requires the measure of the diameter at six or more points around the circumference. The roller must be rotated in its mount in order for these measurements to be made. However, the measurement is still one of diameter using the same measuring devices.

5.1.2 Measurement of Length, End Parallel and End Runout

The measurement of the roller length can best be performed using proximity probes located at both ends as shown schematically in Figure 5.6. The distance, P, between the two probes must be known very accurately. The two measurements, x_1 read by probe #1 and x_2 read by probe #2, are subtracted from P to obtain the roller length, L. The mount which supports the probe must be stable in order to insure that the device remains calibrated. The calibration can easily be performed by using this device to measure a roller having a known length. This so-called "standard" roller can be checked periodically in order to monitor the system calibration.

This technique can be extended so that the end parallel and runout measurements are also obtained. The single probes for measuring length are replaced with a triad of probes at either end as illustrated in Figure 5.7. The figure shows the triangular arrangement of the probes about the circumference of the roller. The location of the probes should coincide with the end runout gauge point located approximately 0.050" in from the edge of the roller. The roller is again positioned in a kinematic mount which serves to locate the axis of the roller in a known position. The three probes at each end measure the position of three points near the circumference of the end planes of the roller. This data can be used to directly calculate the position and orientation of the end planes with respect to the axis of the roller. The data can then be reduced to yield the end runout (which is actually an end squareness measurement), end parallelism and roller length.

5.1.3 Measurement of Crown Drop and Crown Runout

The crown measurements can be approached in the same manner as the diameter and taper measurements described in Section 5.1.1. Either the optical or proximity probe type measurements described in that section could be extended to include the crown measurements. In the case of the proximity probe techniques, an additional set of probes could be situated at the designated gauge points at each end of the roller to measure the crown drop. The crown runout would be determined from these probes when the roller is incrementally rotated to obtain the cylindricity measurement. Similarly, the optical imaging measurement approach could be slightly modified so that the crown region was included in the measurement.

An alternative approach for performing the crown measurements is to employ an optical imaging system which uses a scanning mirror to sweep the image of the edge of the roller across a linear photodiode

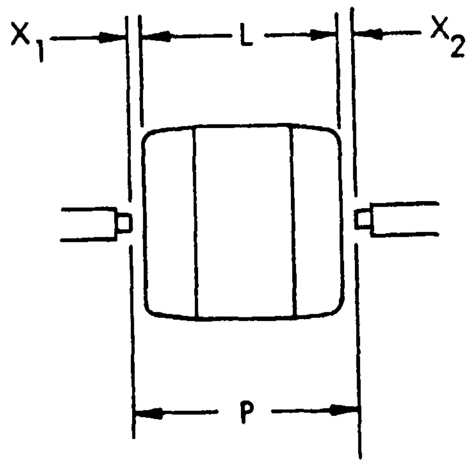


Figure 5.6. Measurement of Roller Length Using Two Proximity Probes. Reading from Probe #1 (x_1) Plus the Reading from Probe #2 (x_2) is Subtracted from the Probe Spacing (P) to Obtain the Roller Length (L).

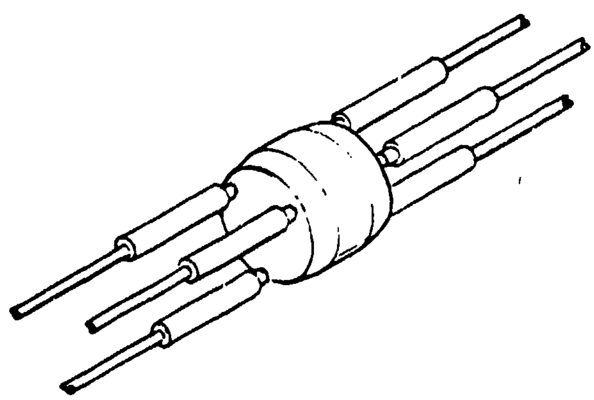


Figure 5.7. Configuration of Three Proximity Probes at Each End of Roller to Obtain Length, End Parallel and End Runout Measurements.

array mounted transversely with respect to the edge. This technique which is also quite suitable for the Group IV and V measurements, is illustrated in Figure 5.8. The high resolution imaging lens projects and magnifies an image of the edge into the plane where the detector array is mounted. The mirror located in the optical path serves to move the image across the array. The output of the array is used to determine the radial coordinate of each point of the edge while the axial coordinate is determined from the position of the scanning mirror. When the mirror is set to scan the flat cylindrical portion of the roller, the detector elements A through D (as illustrated in Figure 5.9) will record no light, while elements D through E will record maximum light intensity. As the mirror scans toward the end of the roller, the transition of dark to light as recorded by the detector will change from D towards A. At the crown drop gauge point, the location of the transition point (C) will yield the crown drop measurement. The locations of the ends of the roller are also determined to serve as a check on the location of the crown gauge points. The runout measurement still requires rotation of the roller in its mount with repetitive measurements. This technique has the advantage of being able to measure the Group V measurements simultaneously with no additional hardware requirements.

5.1.4 Measurement of Corner Breakout and Corner Runout

Because of the simple geometry of the roller corners, the measurement of the corner breakouts can best be performed using a scanned linear photodiode array as described in Section 5.1.3. For this application, the imaging lens is chosen to just cover the corner area, thereby permitting use of a higher magnification than used for the crown measurements. Greater reliability can be added by employing two arrays mounted and scanned perpendicular to each other. While being somewhat redundant, the added information makes it easier to precisely pinpoint the corner breakout location. Again, the runout measurement is performed by rotating the roller and making repetitive measurements about its circumference. An alternative approach for profiling the corners is to employ an imaging tube which inputs into an

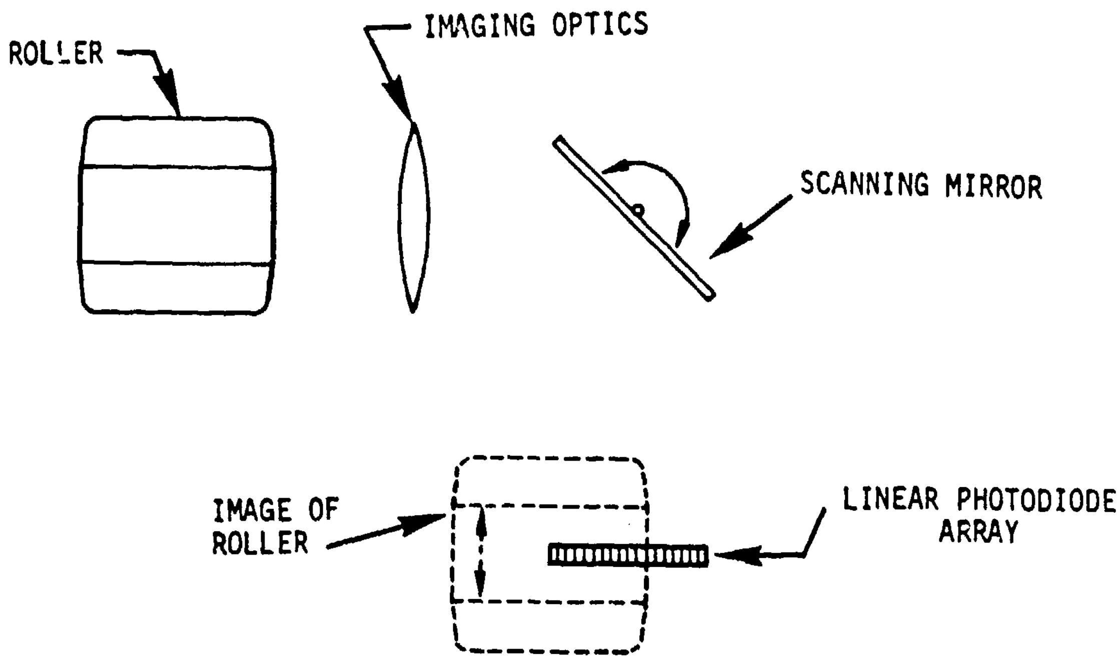


Figure 5.8. Scanned Optical Imaging System for Determining Contour of Rollers Edge

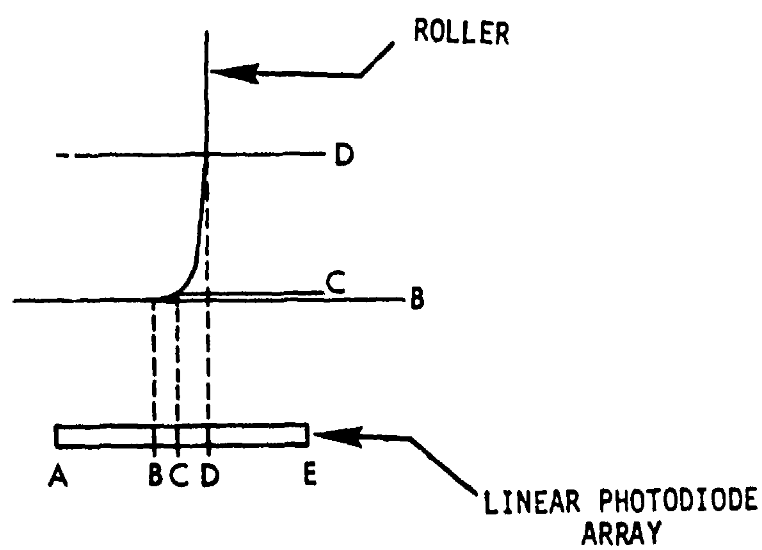


Figure 5.9. Correspondence Between Location on Roller and Light-Dark Transition on Photodiode Array

image analysis computer. This approach, however, is more sophisticated (and thus expensive) than necessary for obtaining the required data.

5.1.5 Measurement of Flat Length and Flat Centrality

The flat measurements are readily determined using the scanned linear photodiode array system described in Section 5.1.3. The flat length can be calculated directly by monitoring the locations of the scanning mirror where the light-dark transition begins to change from its constant value over the flat region. If the system is not aligned correctly with respect to the axis of the roller, or if the roller exhibits a significant degree of OD taper, then the scan across the flat will yield a constant change vs. position. The end of the flat will be detected when this change begins to accelerate into the crown slope. By scanning the entire length of the roller, the locations of the ends with respect to the flat are determined, thus yielding the flat centrality. Because the required precision of these measurements is relatively low, they are not as difficult to perform as the other measurements.

5.1.6 Measurement of Surface Finish

The tumbling process currently employed to produce the fine surface finish on rollers does not pose any particular problems in meeting the required tolerance. Current inspection techniques consist of spot checking rollers from each batch. Since this procedure has been effective, the cost of adding surface finish inspection to the measurement instrument may not be justified. However, this problem has been well researched and several optical procedures are available for measuring surface finish. In particular, it has been shown that Coherent Surface Analysis can accurately determine surface roughness in the range of 0.5 to 10 microinches of a non-flat object (Reference 5). This technique essentially involves the reflection of a laser beam off of the roller surface and the subsequent analysis of the resulting diffraction pattern. This technique can also be used to identify surface scratches and other blemishes.

5.2 Integrated Roller Inspection and Classification System

This section describes the requirements and constraints which apply to the integrating of the gauging mechanism into a complete system and presents a conceptual system which meets those requirements. Roller handling just after the final manufacturing process (tumbling) can be manual since the total number of precision rollers produced is relatively small and automated handling at this point would not be cost-effective. However, from the point where the parts emerge from the initial cleaning, the roller handling should be automated to prevent dirt and thermal contamination of the roller as it enters the gauging and classifying operations.

5.2.1 System Requirements and Constraints

A number of environmental constraints must be considered in the design of the system if it is to function properly. It is necessary to filter the air entering the system to insure that no dust, oil film or particulate matter larger than approximately 1 microinch be present on the roller surface when it is measured. The temperature and humidity must remain above the dew point in order to inhibit the formation of water condensation on the roller surface to avoid corrosion. Furthermore, the roller must be thermally stabilized to within 0.1°F as it enters the measuring station so that thermal expansion effects can be neglected. The cleaning and drying operation must not affect the thermal equilibrium of the roller.

A primary system requirement is adaptability to handle the variety of roller sizes and configurations which are encountered in a production situation. The system must be capable of measuring rollers which range from 5 mm to 30 mm in size. Most of the rollers are "square", i.e., their length equals their diameter. However, other configurations must be handled as well. Fully crown or uncrowned rollers may be encountered as well as the partially crowned rollers discussed here. In order to protect the rollers from damage, they must not impact metal surfaces or other rollers during the entire sequence from final tumbling through final classification and assembly. In particular, extreme care must be taken in transferring the rollers in and out of the inspection stations. Finally, the mechanism must function at a speed which will permit an inspection rate of several hundred rollers per hour.

5.2.2 System Concept

Figure 5.10 illustrates a concept for an automated roller inspection machine. By combining all gauging operations into one device, the risk of dirt or thermal contamination is minimized since no manual handling or storage occurs between measuring stations. The integrated system is composed of the following elements

1. Cartridge receiver and ejector mechanism.
2. Solvent de-oiler and air dry section.
3. Gauge fixture and measurement system.
4. Re-oiler.
5. Data processing and classification system.
6. Roller sorting mechanism.
7. Air conditioning and filtering unit.

The overall system is incorporated around a massive platform which is supported by shock and vibration isolation dampers. The air conditioner/filter unit is independently mounted to the foundation to minimize transmitting vibrations to the gauging mechanism.

5.2.3 System Operation

An intriguing approach to the problem of handling the rollers involves the use of cartridges. The cartridges will be made of a rigid polymeric material with dividers between the rollers to prevent metal-to-metal contact. Each cartridge will contain up to thirty-six rollers. The cartridge will be used to deliver rollers to the gauging system and also to receive classified rollers at the exit points of the system. Cartridges of cleaned and oiled rollers are presented manually to the entrance of the inspection system through a slot at the side of the machine. Once inside, the cartridges are in a temperature controlled, filtered air environment. A slight positive pressure excludes outside

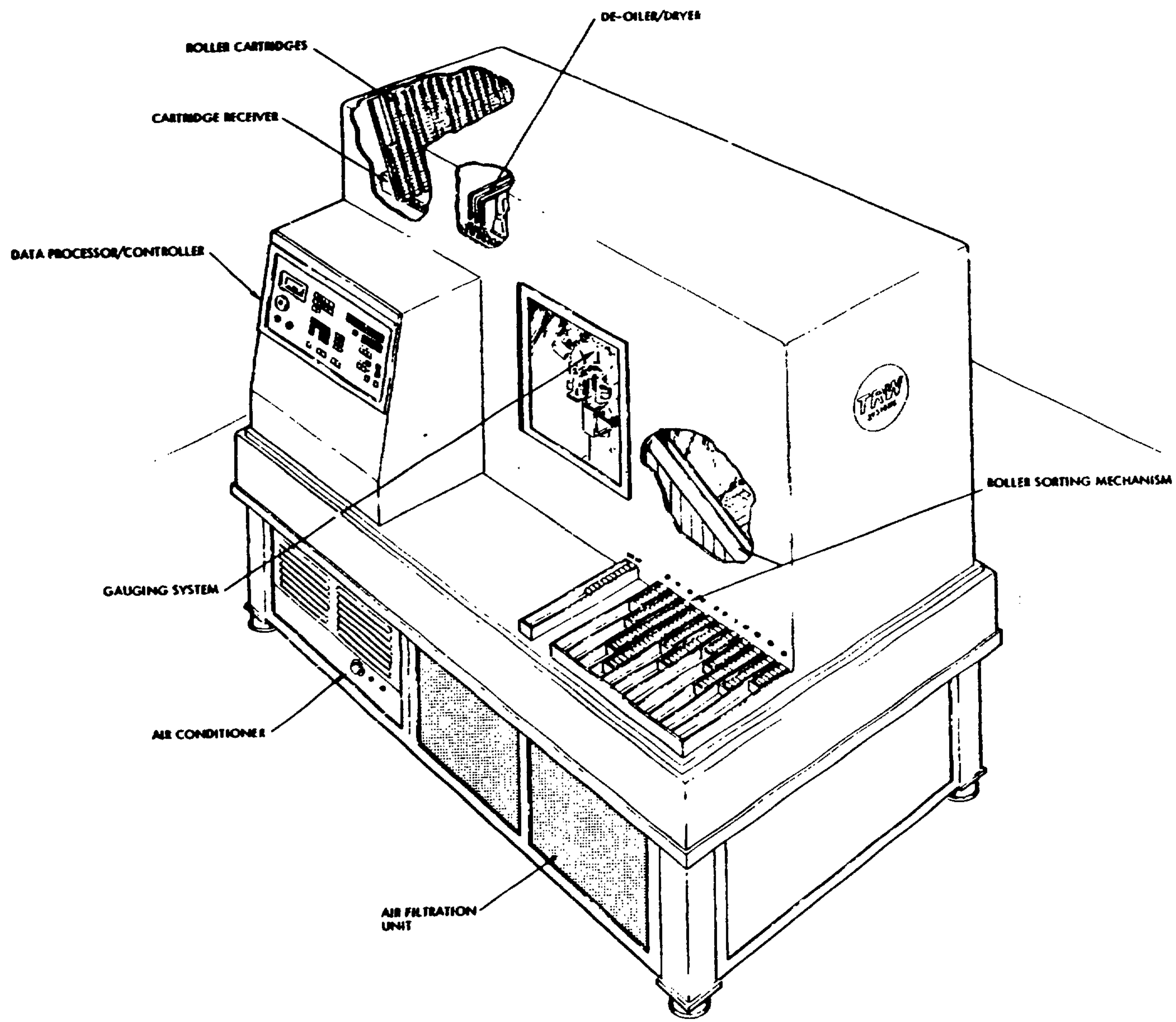


Figure 5.10. Automated Roller Inspection System Concept

contamination. Side-by-side storage of the cartridges allows preloading of the machine with up to several hours worth of rollers and allows enough time for temperature stabilization.

Rollers are ejected sequentially from the cartridges onto a pocketed transfer belt where they receive a solvent spray and air dry to remove the oil film. Temperature of the spray and the drying air are controlled to minimize any temperature changes due to the evaporation of the solvent. Empty cartridges are ejected to a receiving tray and are used to receive classified rollers at the exit of the gauging machine.

The transfer belt presents the rollers to the gauging mechanism turntable as shown in Figure 5.11, dropping into the lined slot of the turntable at position 1.

A motor with controls to permit one revolution-per-cycle operation is connected through a geneva drive and suitable gear train to operate the gauging turntable. The motor will be de-energized during gauging operations to eliminate vibrations. The turntable, with twelve pockets, indexes 30° per cycle. It rotates in the vertical plane to utilize gravity in the handling of the rollers at the three measuring stations which provide all of the data required for complete classification of the rollers.

Each of the twelve pockets in the turntable contains a spring loaded plunger with the plunger normally retracted. Solenoids are used at stations 2, 3, and 4 to actuate the plunger and insert the roller into the measuring fixture. At station 2, the roller is inserted into the kinematic mount shown in Figure 5.12 and is held under very accurately controlled pressure from the solenoid. With the roller in place against the radial supports, an air cylinder operates a plunger with a rubber cap end piece which is driven axially against the free end of the roller and holds it in place against the axial support. At this time, readings are taken from the transducer array as described in Section 5.1.1. Here an additional set of transducers has been added to provide additional resolution for determining the true position of

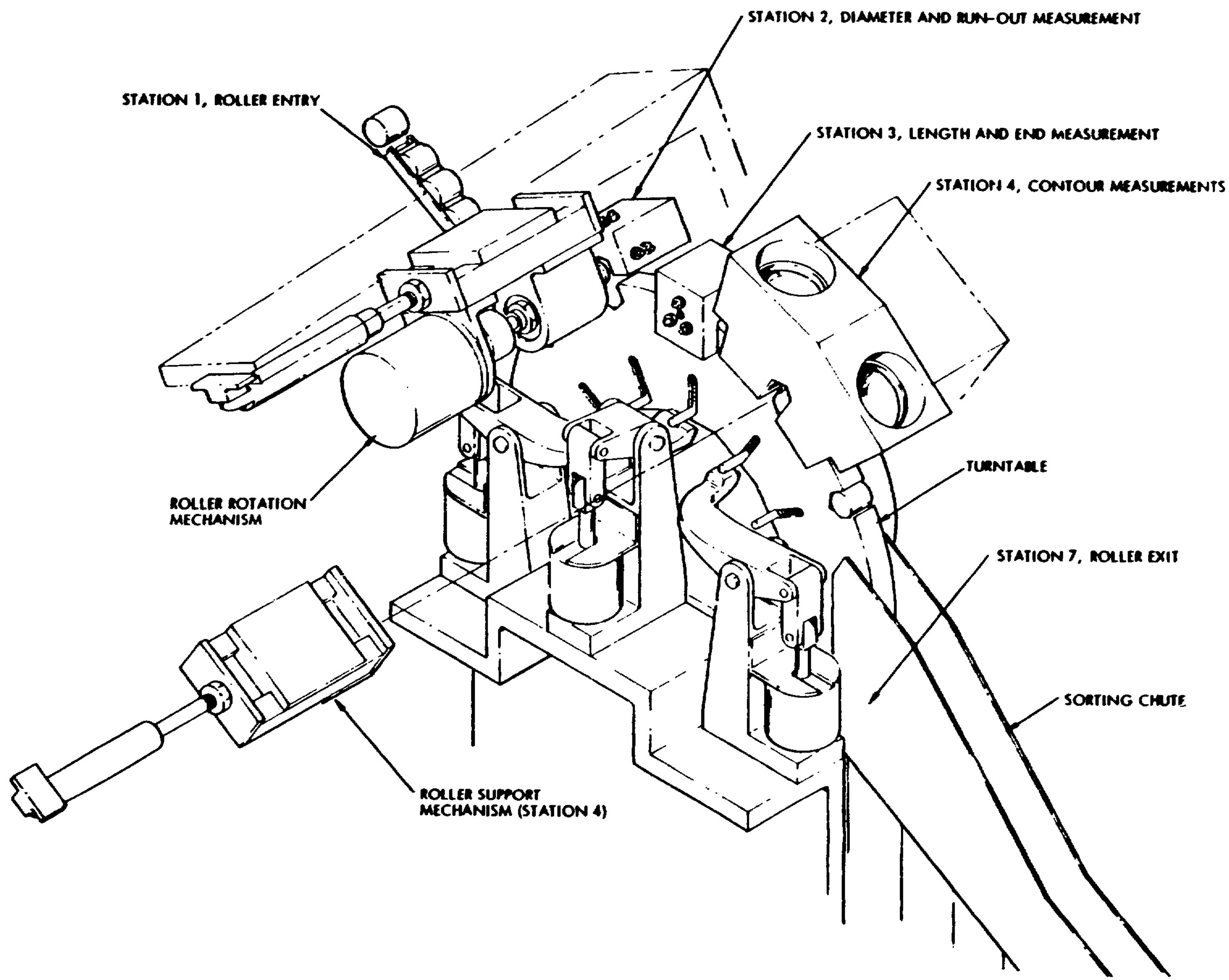


Figure 5.11. Roller Inspection Subsystem Including Turntable and Three Measurement Stations

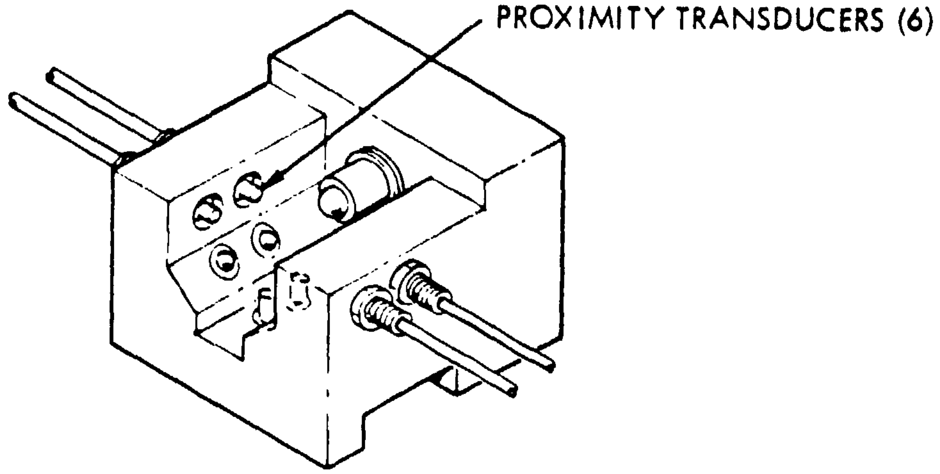


Figure 5.12. Measurement Station #2 with Proximity Probes Arranged for the Diameter (Group I) Measurements

the roller. After the data are read, pressure from the solenoid is removed and the roller is rotated 60° by means of a stepping motor attached to the axial plunger (Figure 5.11). The solenoid is re-activated and a new set of data are read. This sequence is repeated five times and the six sets of data used by the computer to calculate diameter, out-of-roundness, and taper of the roller. After the measurement cycle, the axial plunger is retracted and the solenoid de-energized, allowing the roller to drop into the pocket. The turntable is then rotated 30°.

At station 3, a second solenoid inserts the roller into the length and end squareness gauge fixture. At this station the roller is held in place by the solenoid and an axial plunger (Figure 5.13) but is not rotated. Six transducers develop the data used for the length and end squareness calculations as described in Section 5.1.2.

At station 4, the roller is moved up into the kinematic mount of the optical gauge fixture which measures crown drop, corner radius and flat length. A view through the cross-section of this fixture is

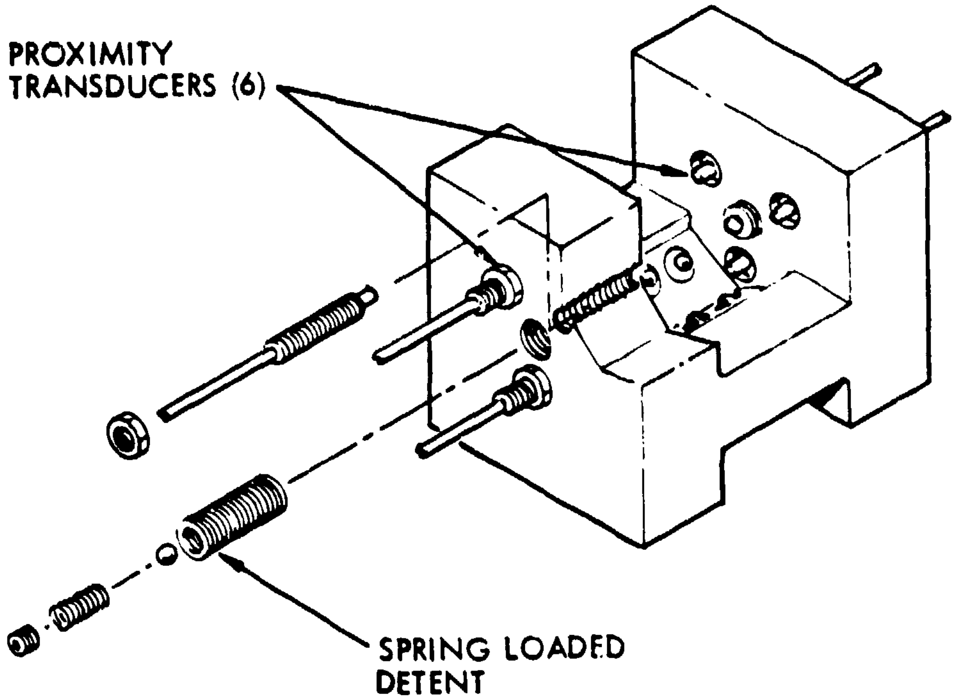


Figure 5.13. Measurement Station #3 with Proximity Probes Arranged for the Length (Group II) Measurements

shown in Figure 5.14. When positioned, the profile of the roller is detected by the optical system. Operation at this station is similar to that at station 2 with the mechanism of Figure 5.11 used to hold the roller axially in position. Rotation for multiple measurements of the above parameters can be accomplished by use of a stepping motor as at station 2.

5.2.4 Classification of Rollers

Information developed at the measurement stations (2,3, and 4) is utilized by the computer to classify the roller by length and diameter and to accept or reject on the basis of end squareness, flat length, corner radius, out-of-roundness, etc. The computer also tracks and controls the position of the turntable so that, as the roller reaches position 7 and is dropped into the sorting chute, the appropriate gate will be opened to divert the roller to the receiving

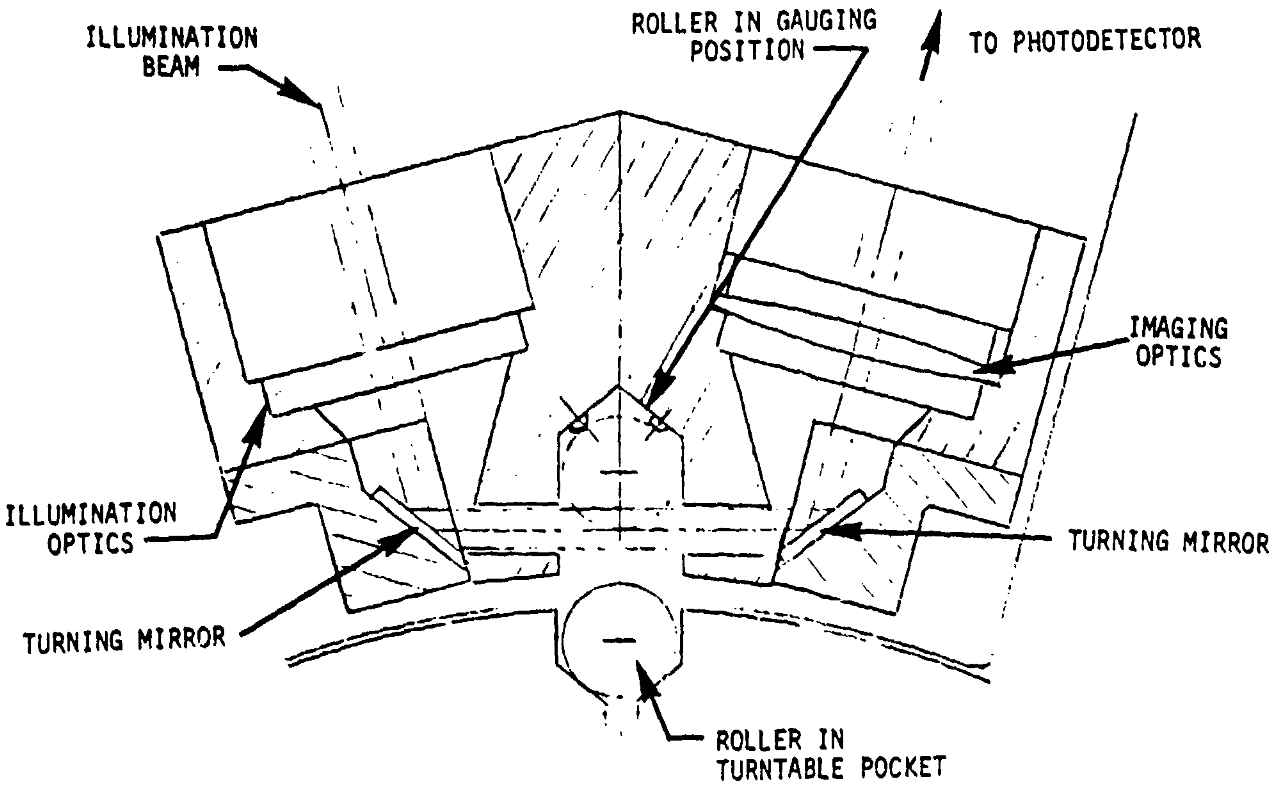


Figure 5.14. Cross-section of the Optical Gauge Fixture (Station #4) Showing Optical Path for Profiling the Roller

cartridge. The sorting chutes are all lined and are equipped with retarders to prevent damage to the rollers. Only one roller will be in the sorter at any given time. As the receiving cartridges exit the sorting mechanism, the rollers are re-oiled to prevent corrosion in subsequent operations.

With the flexibility afforded by the data processing system, several alternate sorting methods may be used. Each classification of roller length by diameter can be segregated in separate cartridges. Alternatively, rollers can be segregated by length in a given cartridge with the diameter of each roller indicated on the readout or recorded on a magnetic strip integral to the cartridge. Method 1 could require as many as 128 separate cartridges whereas Method 2 could be implemented with only 16 cartridges. A third possibility is the use of a single line of receiving cartridges with all of the classification information on the magnetic strip. In this case, a post-gauging sorter would be utilized.

An additional benefit to be derived from the use of this system is the availability of statistical data, collected in the microcomputer, relating to all of the roller characteristics. This data can be used as a check on the various manufacturing processes. Tolerance trends can be identified so that corrective action can be instituted at a point where the production of rejectable parts can be minimized.

5.2.5 System Features

The important features of the design concept presented here are:

1. Unitized design minimizes storage time and eliminates handling between measurement stations.

2. Entire system operates in a temperature controlled, air-filtered environment.

3. Each roller is classified in the order in which it enters the machine. This can be a powerful aid in developing feedback data to manufacturing, particularly if steps are taken in manufacturing to achieve time sequential order of the rollers.

4. Different sized rollers can be accommodated by changing the fixture modules and the pocket inserts on the turntable.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The program objective of developing a fully automated roller inspection system utilizing current technology is achievable. The survey of precision measurement techniques yielded a number of non-contacting devices, each of which is capable of meeting at least some of the measurement objectives. Although no technique was identified which could adequately measure all of the roller characteristics, at least two techniques were found for measuring each characteristic. This redundancy allows the measurements to be grouped so that all of the characteristics can be measured at three stations. A system concept based upon this principle has been outlined. In addition to the inspection of the rollers, all of the peripheral operations are incorporated into this system. These include cleaning, temperature stabilization, re-oiling, sorting and data accumulation. The system is completely self-contained and requires minimal human supervision. The statistical data acquired can be used for monitoring manufacturing processes in order to optimize the production of acceptable rollers.

It is recommended that development of a roller inspection system such as the one described herein proceed. The next step is to perform a detailed laboratory analysis to verify the performance capabilities of the candidate measurement devices. In particular, parameters such as signal-to-noise ratio, drift and the affect of environmental factors need to be determined to more certainty than possible using the data supplied by the manufacturers. The data produced by these tests will provide a firm basis for the final selection of the devices to be incorporated into an inspection system.

Based upon the design concept presented in Section 5 of this report, and the results of the laboratory tests of the measurement devices, the individual measurement stations can be designed. Laboratory breadboard versions of these stations can then be constructed and their effectiveness for measuring the various roller characteristics demonstrated.

After the demonstration of the breadboard subsystems, design of a prototype inspection system can be initiated. This system will then be fabricated, assembled and finally tested to determine its effectiveness to adequately inspect high speed bearing rollers.

REFERENCES

1. "Measurement of Out-of-Roundness", The American Society of Mechanical Engineers, ANSI B89.3.1-1972.

2. C. T. Van Degrift, "A Sensitive Displacement Transducer Using an Extremely Reentrant 84 MHz Cavity Oscillator", Review of Scientific Instruments, September 1974, pp. 1171-1172.

3. M. Born and E. Wolf, "Principles of Optics", Fifth Edition, Pergamon Press, 1975.

4. W. Weinstein, "Light Distribution in the Image of an Incoherently Illuminated Edge", Journal of the Optical Society of America, Vol. 44, No. 8, 1954, pp. 610-615.

5. T. V. Roszhart, "Holographic Characterization of Ceramics, Part IV", Final Report for Naval Air Systems Command Contract N00019-73-C-0298, December 1974.

APPENDIX A

The following list of manufacturers and suppliers of measurement devices were included in the survey of the state-of-the-art in precision measurement techniques.

A-B Tool Manufacturing Inc.
Highbridge, New Jersey

Action Instruments Co., Inc.
San Diego, California

Adaptive Systems Inc.
Pompano Beach, Florida

Ade Corporation
Watertown, Massachusetts

AEC Magnetics
Cincinnati, Ohio

Aeroflex Laboratories Inc.
Plainview, New York

Airflyte Electronics Co.
Bayonne, New Jersey

A L Design Inc.
Tonawanda, New York

American Mfg. Co., Inc.
King of Prussia, Pennsylvania

Ametek Controls Division
Feasterville, Pennsylvania

ANAC
Menlo Park, California

Anilam Elecs Corp.
Miami, Florida

Arnold Engineering Co.
Columbus, Ohio

Astrosystems, Inc.
Lake Success, New York

Austin Electronics
Roselle, New Jersey

Autech Corporation
Columbus, Ohio

Automatic Timing & Controls Co.
King of Prussia, Pennsylvania

Autometrix
Dayton, Ohio

B & K Instruments Inc.
Cleveland, Ohio

Barber-Colman, Co.
Rockford, Illinois

Battelle Northwest Laboratories
Richland, Washington

BEI Electronics
Little Rock, Arkansas

Bell & Howell
Pasadena, California

Bendix Corporation
South Bend, Indiana

Bendix Corporation
Aerospace Systems Division
Ann Arbor, Michigan

Bently Nevada
Minden, Nevada

Bernes Engineering
Stamford, Connecticut

Binary Controls, Inc.
San Juan Capistrano, California

Biocom
Culver City, California

PRECEDING PAGE BLANK-NOT FILMED

BLH Electronics
Waltham, Massachusetts

Bowmar TIC Inc.
Newbury Park, California

Brunswick Engineering, Inc.
North Brook, Illinois

Bunker Ramo Corporation
Broadview, Illinois

Burleigh Instruments, Inc.
East Rochester, New York

C&A Products, Inc.
Woodside, New York

Camille Bauer Measuring Instruments
Newtown Square, Pennsylvania

Carter Mfg. Corporation
Bolton, Massachusetts

Celesco Transducer Products Inc.
Canoga Park, California

C. J. Enterprises
Tarzana, California

Coleman Systems
Irvine, California

G. L. Collins Corp.
Long Beach, California

Columbia Research Labs Inc.
Woodlyn, Pennsylvania

Computer Instruments Corp.
Hempstead, New York

Conrac Corporation
Duarte, California

Consolidated Airborne Systems, Inc.
Holtsville, New York

Harrison R. Cooper Systems, Inc.
Salt Lake City, Utah

Courter Inc.
Boyne City, Michigan

Curry Engineering Co.
N. Hollywood, California

Cutler Controls, Inc.
Horsham, Pennsylvania

Daniel Industries Inc.
Houston, Texas

Datacraft Inc.
Gardena, California

Datametrics
N. Billerica, Massachusetts

Data Technology Inc.
Woburn, Massachusetts

DAVCO Mfg. Co.
Morristown, New Jersey

Davidson Optronics Inc.
West Covina, California

Daytronic Corporation
Dayton, Ohio

DelElectronics
Mt. Vernon, New York

Denison, R. B. Inc.
Bedford, Ohio

Diffracto, Ltd.
Troy, Michigan

Disa Electronics
Franklin Lakes, New Jersey

Disc Instruments Inc.
Costa Mesa, California

Drexelbrook Engineering Co.
Horsham, Pennsylvania

Dunlap Instrument Corp.
Cape Girardeau, Missouri

Dymac
San Diego, California

Dynamics Research
Wilmington, Massachusette

Dynapar Corporation
Gurnee, Illinois

Ealing
Cambridge, Massachusetts

Elec. Counters & Controls Inc.
Mundelein, Illinois

Electric Tachometer Corporation
Philadelphia, Pennsylvania

Electro Corp.
Sarasota, Florida

Electronic Automation Inc.
Grand Rapids, Michigan

Electro Sonic Control Inc.
Manteca, California

EMR Schlumberger
Princeton, New Jersey

Encore Electronics Inc.
Saratoga Springs, New York

Entran Devices, Inc.
Little Falls, New Jersey

Envirotech Corporation
Hauppauge, New York

EOCOM Corporation
Irvine, California

Ethyl Intertech Corporation
Princeton, New Jersey

Fairchild Semiconductor
Mountain View, California

Farrand Controls Inc.
Valhalla, New York

Federal Products Corporation
Providence, Rhode Island

FLC Inc.
Jackson, Michigan

Flight Research
Richmond, Virginia

Foxboro
Foxboro, Massachusetts

FSI/Fork Standards Inc.
West Chicago, Illinois

Galileo Electro-Optics Corporation
Sturbridge, Massachusetts

Geier & Bluhm Inc.
Troy, New York

Gilson Medical Electronics
Middleton, Wisconsin

GMR Inc.
Rochester, New York

Gould
Cleveland, Ohio

Grass Instrument
Quincy, Massachusetts

GSE Inc.
Farmington Hills, Michigan

Gulton Ind.
Costa Mesa, California

Hamamatsu Corporation
Middlesex, New Jersey

HDL Research Lab
Houston, Texas

Heidenhain Corporation
Arlington Heights, Illinois

Helm Instrument Co., Inc.
Toledo, Ohio

Hewlett-Packard
Palo Alto, California

HH Controls Co., Inc.
Arlington, Massachusetts

Holograf Div/Optics Tech.
Redwood City, California

Honeywell
Minneapolis, Minnesota

Honeywell Process Control Div.
Fort Washington, Pennsylvania

HSI Inc.
Houston, Texas

Hughes Aircraft Co.
Culver City, California

Humphrey, Inc.
San Diego, California

Hy-Temp Transducers
Philadelphia, Pennsylvania

IKL Inc.
Newport Beach, California

Illinois Tool Works Inc.
Chicago, Illinois

Impact-O-Graph Corp.
Bedford, Ohio

Incor Inc.
W. Babylon, New York

Indikon Co., Inc.
Watertown, Massachusetts

Industrial Optical Laboratory Inc.
Bloomfield, New Jersey

Instron Corporation
Canton, Massachusetts

Instrumentation & Control Sys. Inc.
Addison, Illinois

IRD Mechanalysis Inc.
Columbus, Ohio

ISC Magnetics Division
Plainview, New York

Itek
Newton, Massachusetts

ITT Industrial & Automation Systems
Plymouth, Michigan

Jackson Bros (London) Ltd
Croydon CR94DG England

Jones & Lamson
Springfield, Vermont

Jordon Controls Inc.
Milwaukee, Wisconsin

Kaman Sciences Corporation
Colorado Springs, Colorado

Kavlico Corporation
Chatsworth, California

Walter Kidde & Co., Inc.
Pawcatuck, Rhode Island

James Kimberley Inc.
Newtown Square, Pennsylvania

Kinetic Systems Inc.
Waltham, Massachusetts

Kistler-Morse Corporation
Bellevue, Massachusetts

Kyowa Elec. Instruments Co., Ltd.
Tokyc, Japan

Labtronics
Port Washington, New York

Lafayette Instrument
Lafayette, Indiana

Larson Aero Development
Concord, California

Leach Corp., Relay Division
Los Angeles, California

Leeds & Northrup
North Wales, Pennsylvania

LEL Co.
Cresskill, New Jersey

Licon Division, Illinois Tool
Chicago, Illinois

Lion Precision Corporation
Newton, Massachusetts

Litton Sys. Inc.
Mt. Vernon, New York

Los Angeles Scientific Instru. Co.
Los Angeles, California

Martin-Decker Co.
Santa Ana, California

Mechanical Technology Inc.
Latham, New York

Metritape, Inc.
W. Concord, Massachusetts

Metrix Instrument Co.
Houston, Texas

Metrologic Instruments Inc.
Bellmawr, New Jersey

Micro Surface Engineering
Los Angeles, California

Micro-Radian Instruments
Garden Grove, California

Micron Instrument Corporation
Plainview, New York

Mid-West Instrument
Troy, Michigan

Mitutoyo Mfg. Co., Ltd
New York, New York

Modern Controls, Inc.
Minneapolis, Minnesota

Monitor Technology
Redwood City, California

Montevideo Technology Inc.
Montevideo, Minnesota

Moxon, Inc.
Irvine, California

Narco Bio-Systems
Houston, Texas

National Controls Corporation
Addison, Illinois

Northern Precision Laboratories, Inc.
Fairfield, New Jersey

Novotechnik KG Offterdinger & Co.
Ostfildern, West Germany

Ocean Research Equipment
Falmouth, Massachusetts

Omega Industrial Products
Monroe, Washington

Ono Sokki Co., Ltd
Tokyo, Japan

Optical Electronics Inc.
Tucson, Arizona

Optics International
Tenafly, New Jersey

Optograms, Inc.
Oakland, New Jersey

Optomechanisms Co. of America, Inc.
Brooklyn, New York

Optron Corporation
Woodbridge, Connecticut

Parametrics
S. Orange, Connecticut

Peerless Nuclear Corporation
Stamford, Connecticut

Perkin Elmer, Bollen-Chiven Civ.
S. Pasadena, California

Permalink Corporation
Newtown Square, Pennsylvania

Philips Ind.
Eindhoven, Netherlands

Phipps & Bird
Richmond, Virginia

Photobell Co.
New York, New York

Photomation Inc.
Mountain View, California

Pickering & Co., Inc.
Plainview, New York

Pneumo Precision
Keene, New Hampshire

Poly-Scientific, Litton
Blacksburg, Virginia

Post Electronic Products, Inc.
Beverly, Massachusetts

Power Instruments
Skokie, Illinois

Printed Motors Division/Kollmorgen
Glen Cove, New York

Production Measurements Corp.
Hilliard, Ohio

Rank Precision Industries, Inc.
Chicago, Illinois

Reliance Electric Co.
Cleveland, Ohio

Renco Corporation
Goleta, California

Research, Inc.
Eden Prairie, Minnesota

Reticon
Sunnyvale, California

Robinson-Halpern Co.
Plymouth Meeting, Pennsylvania

Ronan Engineering Co.
Woodland Hills, California

Rotiform Corporation
Inglewood, California

Schaevitz Engineering
Camden, New Jersey

Scientific Technology Inc.
Mountain View, California

Senso-Metrics, Inc.
Van Nuys, California

Sensor Corporation
Scottdale, Pennsylvania

Sensor Technology Inc.
Chatsworth, California

Sentrol Systems Inc.
Atlanta, Georgia

Sequential Information Sys. Inc.
Elmsford, New York

Siemon Manufacturing
Wayne, Illinois

Sierracin/Thermal Systems
Los Angeles, California

Siltran Digital
Silverado, California

Singer Co.
Little Falls, New Jersey

Skan-A-Matic Corp.
Elbridge, New York

Sloan Technology Corporation
Santa Barbara, California

Slocomb, J. T., Co.
So. Glastonbury, Connecticut

Solid State Electronics Corporation
Sepulveda, California

Sony Magnescale Inc.
Tokyo, Japan

Spectronics Inc.
Richardson, Texas

Speed Detectors Inc.
Bedford, Ohio

W. F. Spengnether Instrument Co.
St. Louis, Missouri

Sprague Electric Co.
N. Adams, Massachusetts

L. S. Starret Co.
Athol, Massachusetts

Statham Instruments
Oxnard, California

Strainsert Co.
W. Conshohocken, Pennsylvania

Sys-Tec, Inc.
New Brighton, Minnesota

Systron Donner
Concord, California

Tann Controls Co.
Detroit, Michigan

Techmet
Dayton, Ohio

Teledyne Geotech
Garland, Texas

Teledyne Gurley
Troy, New York

TempoSonics
Plainview, New York

Tensitron Inc.
Harvard, Massachusetts

Texas Instruments Inc.
Dallas, Texas

Theta Industries, Inc.
Port Washington, New York

Theta Instrument Corporation
Fairfield, New Jersey

Time-Trol, Inc.
Van Nuys, California

Transducer Sys. Inc.
Willow Grove, Pennsylvania

Transmagnetics, Inc.
Farmingdale, New York

Trans-Tek Inc.
Ellington, Connecticut

TSN Company, Inc.
Tucson, Arizona

Unholtz-Dickie Corporation
Hamden, Connecticut

Unimetrics
Anaheim, California

United Detector Technology Inc.
Santa Monica, California

Veeder-Root
Hartford, Connecticut

Vibro-Meter Corporation
Torrance, California

Vickers Instruments Inc. (McBain)
Chatsworth, California

Vitec, Inc.
Cleveland, Ohio

Waters Manufacturing, Inc.
Wayland, Massachusetts

West Coast Research Corp.
Los Angeles, California

Worner Electronic Devices
Rankin, Illinois

Carl Zeiss, Inc.
New York, New York

Zi-Tech
Palo Alto, California

Zygo Corporation
Middlefield, Connecticut

☆ U. S. GOVERNMENT PRINTING OFFICE: 1977 — 757-001/532